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US Army Corps
of Engineers

USER'S MANUAL AND EXAMPLES FOR GNWAVE

by

Zeki Demirbilek

Coastal Engineering Research Center

DEPARTMENT OF THE ARMY

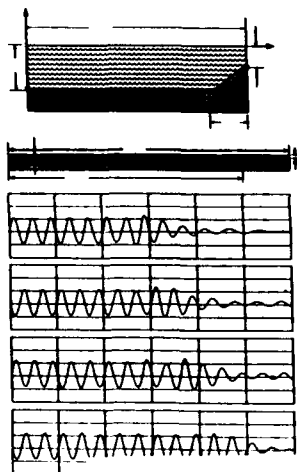
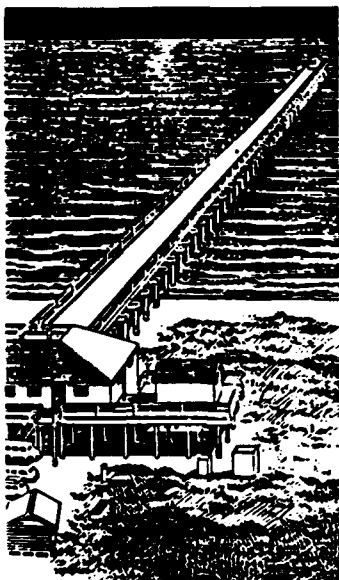
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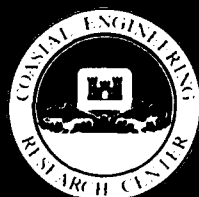
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13. ABSTRACT (Maximum 200 words) This report describes the operation and use of a new numerical model, GNWave. This model was designed to simulate the evolution of a train of two-dimensional waves in waters of arbitrary bottom topography, varying from shallow water to waters of moderate depth. The program uses the Green-Naghdi theory of fluid sheets as its model, and integrates a set of coupled, nonlinear partial differential equations in time to perform the simulation of surface gravity waves. Report 1 in this series, entitled "Application of the Green-Naghdi theory of fluid sheets to shallow water wave problems," contains a detailed description of the mathematical basis of GNWave model. The model GNWave has been shown to reproduce with engineering accuracy the evolution of a wave of permanent form, from small amplitudes up to almost breaking conditions. The numerical model is portable with little or no changes to a wide variety of platforms, and has successfully been tested on high-end PC's and VAX and CRAY mainframe systems. The governing equations were programmed using Fortran as the language. The program consists of a main program and a number of modules to perform the <div style="text-align: right;">(Continued)</div>				
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calculations. A functional flow chart of individual routines involved in the computation is included herein. The main routine directs the sequence of the calculation, including the reading of the input and integration of the equations, and performs some post-processing. The main program is divided into two basic segments: an input portion where the specifications of the problem are read in and echoed to the computer screen, and an integration portion where the equations are integrated one time step at a time. Output is produced at pre-specified instants in the computation stages.

The calculation involves four basic components: generation of waves at the ocean end of the wave tank, enforcement of an appropriate boundary condition at the shore end of the computational domain, solution of the two-point boundary value problem in space at a given instant in time, and integration of the equations in time. Each of these four components requires special techniques, which are discussed in this report to give the user an overview of the flow of information and a flavor for the computation that occurs during a simulation. To further assist the reader in understanding the implementation of the code, the algorithms used for wave generation, the treatment of beach-end boundary conditions, and the spatial and temporal integration of the governing equations are explained in the body of this report. Model input and output features are also presented, together with the procedure for using the program and the re-start mode of operation of the model.

Five example problems typically encountered in the military and civil works areas of the US Army Corps of Engineers are presented. These include collision of waves with a hydraulic spillway gate, waves transforming over an open-ended sloping beach, pseudo-spectral waves passing over a sand bar, random waves propagating through a dredged navigation channel, and regular waves shoaling on a landing beach of uniform slope. The first example problem tests the model's capability for a reflective boundary while the second problem checks the implementation of the transmissive or open type boundary condition. Simulation results for problems 3 and 4 are compared to illustrate the effects of a sand bar on the down-wave progressing in a channel. The last problem provides an opportunity to check the model simulation against physical model test data from a laboratory study conducted at the Danish Hydraulic Institute. The model has been shown to reproduce with engineering accuracy the evolution of regular and irregular wave trains up to the almost breaking condition.

14. (Continued).

Algorithms
Amphibious/landing operations
Coastal processes
Computer models
Input/output
Logistics-Over-the-Shore (LOTS)
Numerical simulation
Wave models

PREFACE

This research study was conducted jointly by the Coastal Engineering Research Center (CERC), US Army Corps of Engineers Waterways Experiment Station (WES), and Ship Research Incorporated (SRI), affiliated with the University of California at Berkeley. The study was authorized under the Time-Dependent Nonlinear Free-Surface Wave Modeling Project as part of the In-House Laboratory Independent Research Program (ILIR), Project A91D, in accordance with guidelines established by the WES Office of Technical Planning and Programs.

The study was performed and the report prepared over the period 1 May 1991 through 1 September 1992 by Dr. Zeki Demirbilek, Research Division (RD), Coastal Oceanography Branch (COB), CERC, and Dr. William C. Webster, Professor of Naval Architecture and Ocean Engineering at the University of California, Berkeley and President of Ship Research Incorporated of Kensington, California. The work was conducted under Purchase Order DACA39-91-M-5515. This is the second in a series of reports presenting the operation and use of a new numerical model to simulate the evolution of surface gravity waves.

This study was performed under the general supervision of Dr. James R. Houston and Mr. Charles C. Calhoun Jr., Director and Assistant Director, CERC, respectively; Mr. H. Lee Butler, Chief, RD, CERC; and under the direct supervision of Dr. Martin C. Miller, Chief, COB, CERC. WES Project Manager during the conduct of this study and the publication of this report was Ms. Mary Vincent.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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USER'S MANUAL AND EXAMPLES FOR GNWAVE

PART I: OVERVIEW

This report is aimed at describing the operation and use of a new computer program, GNWave. This program was designed to simulate the evolution of a train of two-dimensional waves in waters of arbitrary bottom topography, varying from shallow water to waters of moderate depth. The program uses the Green-Naghdi theory of fluid sheets as its model, and integrates these coupled, nonlinear partial differential equations in time to perform the simulation. The model has been shown to reproduce with engineering accuracy the evolution of a wave of permanent form, from small amplitudes up to almost breaking conditions. The program is written in the Fortran language and is portable with little or no modification, to a wide variety of platforms. The program development work was performed on an Apple Macintosh IIfx and the program can run successfully on other high-end PC's or on mainframes.

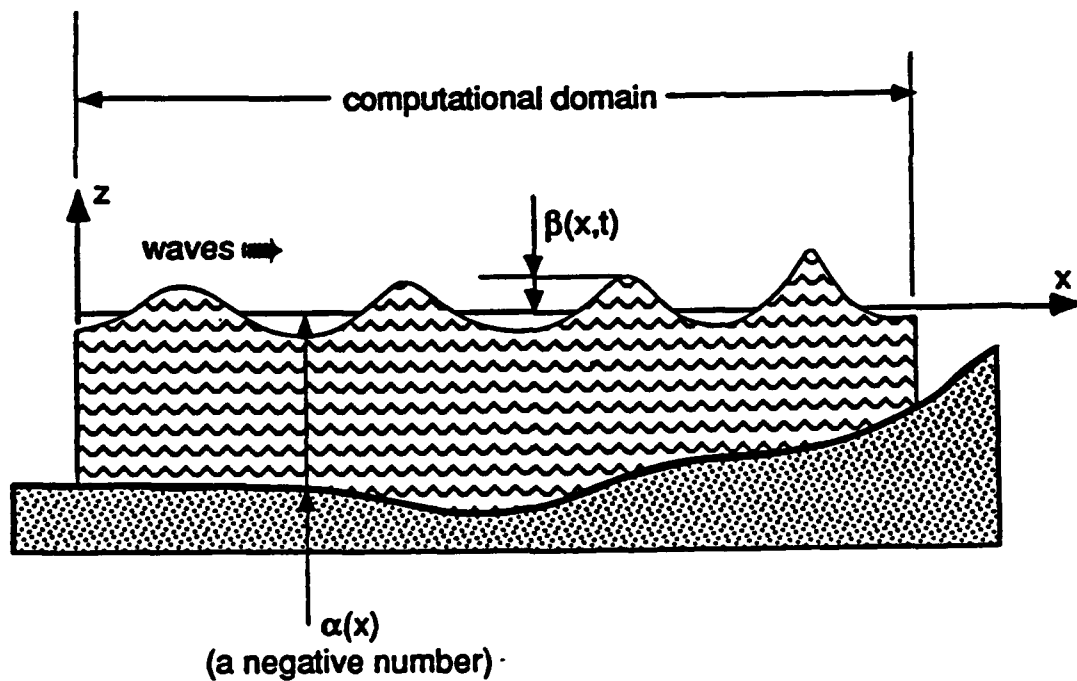


Figure 1. A typical flow for simulation by GNWave

Figure 1 illustrates a typical physical situation which can be investigated. The program is therefore a nonlinear numerical wave tank in which the bottom profile can be arbitrarily chosen and in which wave gauges can be positioned at will. The types of studies

which can be performed are varied and include problems of both military and civil interest. One can study, for instance, the effect of a submerged sandbar on a train of waves approaching a beach (of critical importance during military landings), the reflection of waves and the forces on a seawall or sluice gate (important for the design of civil works projects), or the time history of a wave pressure gage under a train of near-breaking waves (of interest to scientific researchers).

A great deal of care was taken in the programming of this algebraically intensive theory. The code was written using the very rigorous scientific programming standards established by Ship Research, Incorporated, and comments and documentation are included in the code itself. The code was given extensive tests and is believed to be bug-free, but with a code of this complexity, it is not feasible to exercise every possible logic path and, therefore, the possibility exists that some well-hidden bugs remain. The intention was to develop a robust code which can be used widely. Care was taken to make the input and output as simple and as useful as possible.

The sections below outline the GNWAVE code itself, including a brief description of the Green-Naghdi theory which forms the basis of this program, as well as input and output. Several worked examples are presented to demonstrate the uses of the program and its versatility for practical problems of interest to the Corps.

PART II: NUMERICAL MODEL

Theoretical Basis

The theoretical basis for this computer program are the Green-Naghdi Level II shallow-water equations. These equations were originally constructed by Shields (1986) and reported by Shields and Webster (1988). In these original works, the results of the theory were successfully compared with large-amplitude waves of permanent form and with some experiments on wave shoaling (these latter results are reproduced here as a worked example). In the original developments, the equations were expressed with a vertical coordinate which was non-dimensional. In the study, these equations were re-derived in dimensional form, making them more amenable for use in the general simulation code developed here (Demirbilek and Webster 1992).

The Green-Naghdi theory of fluid sheets, hereafter referred to simply as GN theory, was first proposed over 20 years ago. It is an approach which is fundamentally different from the developments in classical wave theory begun by Stokes and Boussinesq in the last century. In classical theory, a perturbation expansion is developed in which the nonlinear boundary conditions are simplified using an assumption that some characteristic of the wave is small (usually the wave amplitude). The field equation (Laplace's equation) is linear and does not require such an expansion. For waves of permanent form this results in a sequence of linear problems of increasing complexity, which can be solved to determine the flow. Since each problem can be solved separately, higher-order solutions (such as Stokes 5th order solutions) are commonly used. For unsteady problems, such as those treated here, perturbation expansions yield evolution equations that become complex and nonlinear with each new order. Few researchers have performed computations with equations of order higher than the lowest order that has nonlinear terms.

GN theory is based on an approach different from the classical approach. In this approach, the form of the velocity variation in the vertical direction across the fluid sheet is assumed to be given. The horizontal coordinate is taken to be x and the vertical coordinate is z . In the Level II equations used in the program, the horizontal velocity is assumed to vary linearly in z and the vertical velocity quadratically in z . Thus, for any x , it is assumed that the horizontal velocity is given by

$$u(x,z,t) = u_0(x,t) + u_1(x,t) z$$

whereas the vertical velocity is expressed as

$$v(x,z,t) = v_0(x,t) + v_1(x,t) z + v_2(x,t) z^2.$$

The equations of motion or governing equations are derived by enforcing exact kinematic and dynamic boundary conditions on the free surface and on the bottom, as well as

conservation of mass and conservation of the 0th and 1st moments of momentum across the sheet (in the vertical direction). These conditions yield eleven coupled partial differential equations, which can be reduced to three rather complicated governing equations by elimination of many of the variables. The remaining dynamic variables are: $\beta(x,t)$, $u_0(x,t)$ and $u_1(x,t)$. These final equations and their derivation can be found in Demirbilek and Webster (1992).

In summary, the GN theory is different from the perturbation approach in that the free surface and bottom boundary conditions are met exactly, whereas the field equation is implicitly approximated. The result is a theory that can predict the shape and behavior of waves up to almost breaking conditions, at least for those cases of waves of permanent form where numerically accurate solutions are known. GN theory breaks down when the particle velocity at the crest equals the wave speed, the criterion for breaking in the exact theory. Limited comparisons with shoaling wave tests have also shown that this theory can reproduce this complicated process.

Computer Code

The governing equations were programmed using Fortran as the language. The program consists of a main program and a number of subroutines to perform the calculation. A functional flow chart of the individual routines involved in the computation is shown in Figure 2 on the following page. The main routine, GNWave, directs the sequence of the calculation including the reading of the input, integration of the equations, and performing the output. The GNWave program is divided into two basic segments: an input portion where the specifications of the problem are read in and echoed to the computer screen, and an integration portion where the equations are integrated one time step at a time. Output is produced in this loop at various, pre-specified instants in the computation. The remainder of this section focuses on the computational aspects of GNWave; the input and output are discussed in separate sections below.

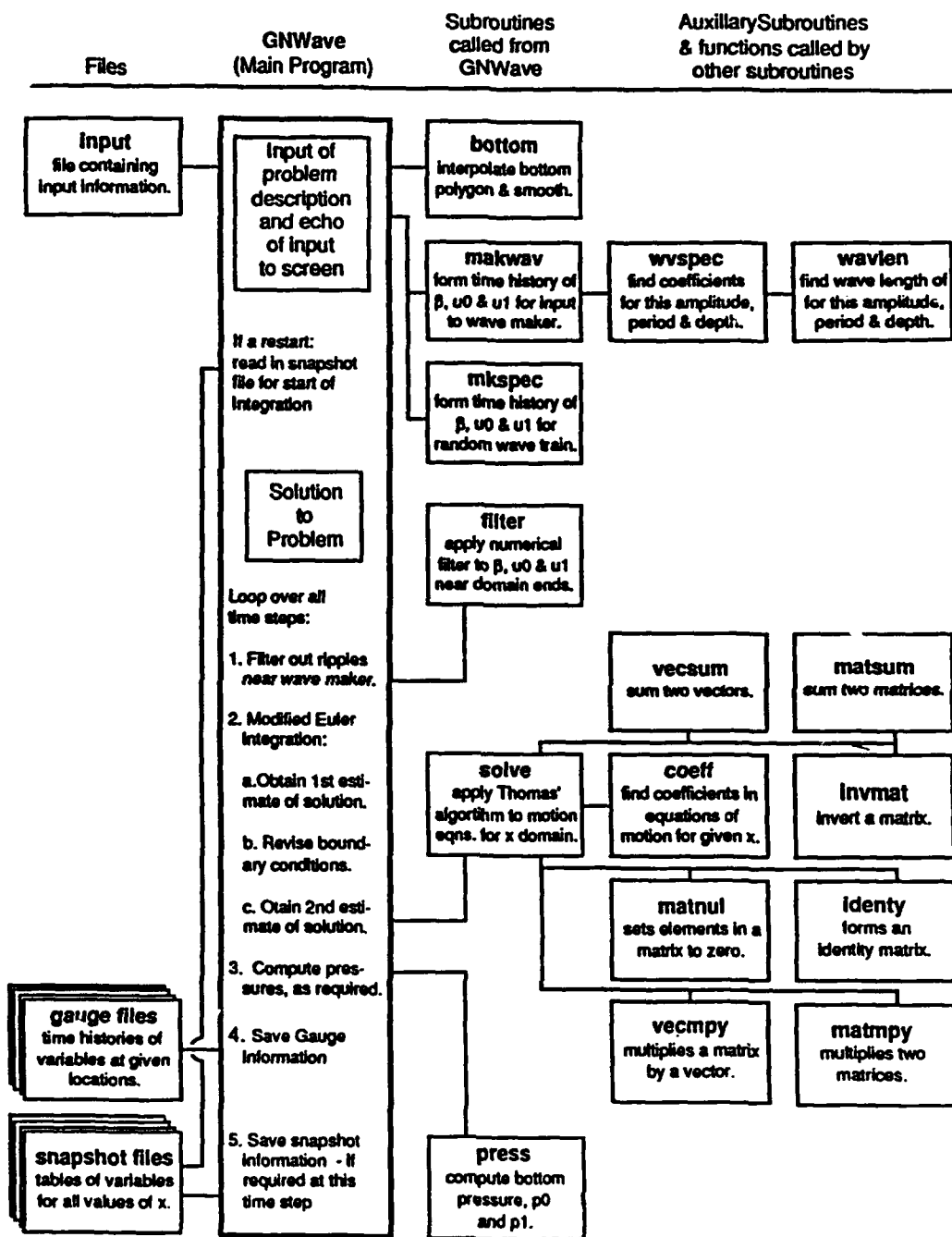


Figure 2. Program level flow chart for GNWAVE

The calculation involves four basic components: generation of waves at the ocean end of the wave tank, enforcement of an appropriate boundary condition at the shore end of the tank, solution of the two-point boundary value problem in space (at a given instant in time), and integration of the equations in time. Each of these four components requires special techniques, which are discussed below. The purpose for this discussion is to give the user an overview of the flow of information and a flavor for the computation that occurs during the simulation. It is not intended to be a step-by-step presentation of the algorithm. The notation used below corresponds, wherever possible, to that used in the actual Fortran code.

To assist the reader in understanding the implementation of the code, the algorithms sections of the code associated with wave generation, the right-hand boundary condition, the spatial integration of the governing equations, and the temporal integration of the governing equations will be described next.

PART III: MODEL ALGORITHMS

Wave Generation

At the beginning of a simulation, the water in the numerical wave tank is quiescent and there are no waves. It is noted in passing that this is the only known exact solution for nonlinear waves passing over an uneven bottom. The computational domain is discretized into equal spatial steps of length dx , leading to ns points. The dx is selected so that at the water depth corresponding to the origin of the computational domain each wave length is $100 dx$ if regular waves are specified; or the shortest wave is $60 dx$ if irregular waves are specified. At each point in the computational domain, spatial derivatives, up to the third derivative, need to be determined for the independent variables¹. To accommodate this need, two additional points are added to the left of the origin of the computational domain and two more points are added to the right end of the computational domain. The points are indexed from $i = 1$ to $ns + 4$, where the computational domain corresponds to the points from $i = 3$ (at $x = 0$) to $i = ns + 2$ (at $x = 1$)².

Waves are to be imposed on the left-hand boundary of the domain and subsequently propagate to the right. In order to facilitate this process, the following approach is adopted. The time discretization, dt , is selected so that $c dt = dx$, where c is the regular wave celerity (for a water depth the same as at the wave maker) or the celerity of the wave of median frequency, if an irregular wave train is selected. With these selections, time histories for each of the three independent variables are constructed. In the case of regular waves, the subroutine **MKWAV** is called. This subroutine calls two other subroutines, **WAVLEN** and **WVSPEC**. **WAVLEN** estimates the wave length of a regular wave of this height and period in the water depth at the wave maker; **WVSPEC** interpolates a series of tables to determine the first five Fourier coefficients of β , u_0 , and u_1 for regular waves of this height and length.

These data are used by **MKWAV** to construct the required time histories of the three

¹ The bottom profile, $a(x)$, must also have third derivatives. As described later in this section, the subroutine **BOTTOM** constructs such a bottom profile.

² The actual wave maker boundary condition is applied to the point $i = n_s + 1$ and, thus, the point $i = n_s + 2$ is the first point in the fluid field. Similarly, the open boundary condition is applied at $i = n_s + 3$, with the point $i = n_s + 2$ being the last point in the fluid field. In the case of a reflection boundary, the point $i = n_s + 2$ is the point of reflection and this is a legitimate fluid field point.

independent variables for $t = 0, dt, 2 dt \dots nt dt$, where $nt dt = t_{max}$. Because the fluid field is initially quiescent, the wave time history is "ramped" so that the wave maker imposes only a little disturbance at first and gradually builds to the full disturbance. The ramp is accomplished by multiplying the time history from $t = 0$ to $t = T$ (the period of the regular wave or the period of the median frequency wave of a spectra) by a bell-shaped function formed by

$$\sin^2[\pi t / (2 T)]$$

This function is 0 and its slope is 0 at $t = 0$, and is 1 and its slope is 0 when $t = T$. This ramp function forms time histories which are continuous and smooth, even at $t = T$.

By construction, this wave time history is identical with the desired spatial history for regular waves and is nearly identical for the case of irregular waves, especially if the spectrum is relatively narrow-banded. For example, for waves of permanent form moving in the positive x -direction, we have

$$\beta(x,t) = \beta(x - c t)$$

and with the choice of $dx = c dt$, we then have

$$\beta[(x_0 + dx) - c t_0] = \beta[x_0 - c (t_0 - dt)]$$

The imposed time history can therefore be used to define $\beta(x,t)$, $u_0(x,t)$ and $u_1(x,t)$ at $i = 1, 2$ and 3 (corresponding to the left-hand edge of the computational domain and the two points outside of the domain). These points provide a boundary value for the GN equations at this end of the computational domain. At each time step, the values of the three independent variables at $i = 1, 2$ and 3 are updated. This process simulates a wave maker on the left-hand edge of the computational domain.

Right-hand Boundary Condition

GNWave is programmed to simulate two different boundary conditions on the right-hand side of the domain: a reflection boundary condition and an open boundary condition. If the waves are perfectly reflected from the right hand boundary, then we require that the boundary at $i = ns + 2$ act as a fluid "mirror". For instance, we set

$$\beta|_{ns+3} = \beta|_{ns+1}$$

for the points outside of the fluid domain on the right hand side, and likewise

$$\beta|_{ns+4} = \beta|_{ns}$$

However, similar conditions must also be set on the horizontal velocity, that is

$$u_o|_{m+3} = -u_o|_{m+1} \text{ and } u_o|_{m+4} = -u_i|_m$$

and

$$u_i|_{m+3} = -u_i|_{m+1}, \text{ and } u_i|_{m+4} = -u_o|_m.$$

That is, at the reflection boundary the wave amplitude is symmetric and the fluid velocity is anti-symmetric (resulting in zero fluid velocity at the reflected boundary). The reflection boundary as stated above is exact if the boundary is vertical and applies equally to linear and nonlinear waves.

The simulation of an open boundary (that is, the simulation of the situation where the waves continue to propagate unfettered beyond the computational domain) is much more difficult. No exact equivalent for this boundary condition is known for nonlinear water waves. In other simulations, a variety of different methods have been used. For the purposes of this study, the Schrödinger condition is adopted, where the wave celerity is assumed known and constant at the right-hand boundary. In this case, one can write simple expressions for the values of the three independent variables at the right-hand edge of the computational domain and the two points just outside of the domain.

Experience has shown that this condition simulates an open boundary condition for a considerable interval of time after the wave train impinges on this boundary. However, experience also shows that if the waves are nonlinear, this condition eventually breaks down and leads to instabilities, lack of conservation of mass in the computational domain, or anomalous wave breaking. There appears to be no rule of thumb which predicts when this breakdown will occur. In forming the open boundary condition for GNWave, the nonlinear celerity of waves of the same period and height as the incoming waves is computed for the water depth where the condition is to be implied. Tests using this condition have been conducted and the results appear to be satisfactory for a limited time after impingement of the wave train on the boundary. Demonstration of this is shown in a worked example below.

Spatial Integration of the Governing Equations

The GN governing equations are partial differential equations, quasi-linear second-order in time and third-order in space. Further, these equations are subject to so-called two-point boundary conditions: a wave maker boundary condition at $i = 2$ and either reflection or open boundary conditions at $i = ns + 2$ or $ns + 3$, respectively. It is mathematically convenient to deal with the spatial problem first and, in this regard, Thomas' algorithm is easily adapted for this purpose (as described in Demirbilek and Webster (1992)). This algorithm is contained in subroutine `SOLVE` (see Figure 2). Execution of the algorithm requires several vector and matrix operations and these are performed by separate simple subroutines as shown in this figure. The coefficients which define the partial differential

equations are evaluated in another subroutine called **COEFF**.

Temporal Integration of the Governing Equations

The output from **SOLVE** is the first time derivatives of the three independent variables at each point in the computational domain. The value of the variables at the next time step is determined by using a modified Euler integration which is second-order accurate. The flow near the wave maker and near the right-hand boundary (if an open boundary is used) suffers from an alternate point instability. That is, if not corrected, the values of the three independent variables tend to oscillate high and low at neighboring points on the finite difference grid. A modest smoothing of the first few and the last few points in the computational domain is sufficient to eliminate this cosmetic blemish. This smoothing is accomplished in the subroutine **FILTER**. For programming reasons, this subroutine is called before **SOLVE** is called.

Finally, whenever output is performed, three additional dependent variables, \bar{p} , p_0 , and p_1 are computed in the subroutine **PRESS**. These variables are the pressure in the fluid field at the pressure gage, the integrated pressure (from the ocean bottom to the crest of the wave) and the first moment of this pressure (taken about the undisturbed free surface level).

The integration continues until either the maximum specified time, t_{max} , for the simulation is reached or until a wave breaks (this is exhibited by a failure of the matrix inversion in the Thomas algorithm).

PART IV: MODEL INPUT

The input file communicates to the program the type of problem to be solved, the wave system to be created by the wave maker, the output desired, and the geometry of the numerical wave tank.

Before the former quantities are discussed, it is necessary to specify the geometry of the wave tank. The bottom of the tank does not need to be flat, but can be a complex shape. On the other hand, typical problems may involve a spatial discretization with thousands of points and it is not practical to require input of the local depth for this number of points. As a result, a simplification was adopted. The bottom profile is input as a polygonal shape, formed as a series of straight lines connecting a sequence of arbitrarily spaced nodes. Figure 3 shows this geometry.

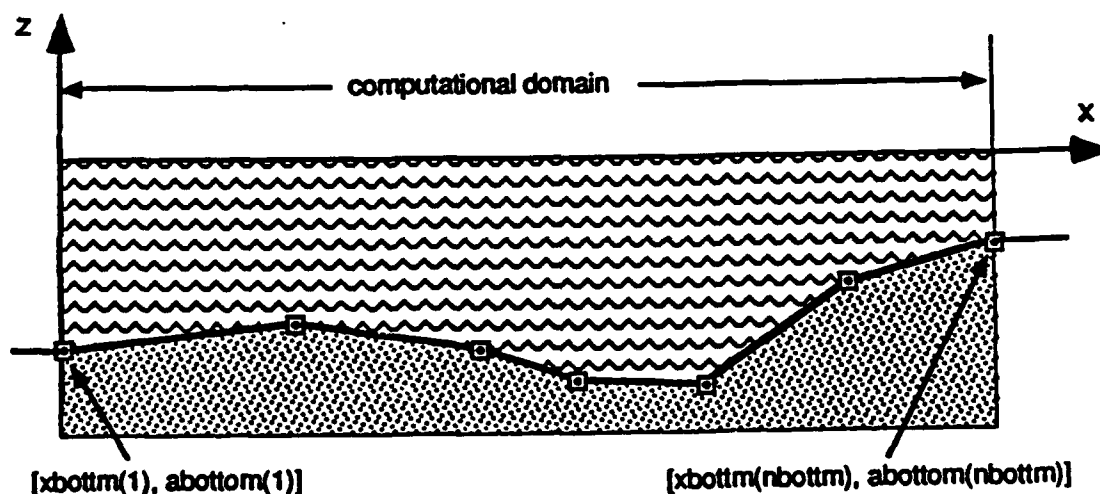


Figure 3. Schematic of the nodes of the polygonal bottom description

The subroutine `BOTTOM` uses this polygonal shape to determine the water depth, $a(x)$, at each of the individual finite difference nodes (from $i = 1$ to $i = ns + 4$). If the value of x for a given node falls outside of the range of bottom data, then $a(x)$ is assumed to be the same as that of the closest input bottom data point. If the value of x falls within the specified bottom data, a linear interpolation between the two closest bottom data points is used. Since the polygon does not have even second derivatives at the corners and since the theory involves derivatives up to and including the third derivative of $a(x)$, the final set of interpolated values of $a(x)$ is smoothed using a numerical filter.

An attempt was made to make the input as simple as possible without compromising the ability of the program to do useful analyses. The "input" file is a flat text file. The name of this file is not important, as the user will be asked by the program to specify it. Figure 4, below, shows the input for a sample problem shown later in this report. Input information in this file is confined to the first 60 columns of the file and the remaining columns are used for comments, a practice which is highly recommended. The "input" file contains the following information³ :

Collision Against Hydraulic Gate	Title
English	units (En or SI)
reflection	rhs b.c. (op or re)
1200.00000	x-domain
180.00000	t-domain
13	# of snapshots
snap1 60.00000	snapshot title & time
snap2 70.00000	snapshot title & time
snap3 80.00000	snapshot title & time
snap4 90.00000	snapshot title & time
snap5 100.00000	snapshot title & time
snap6 110.00000	snapshot title & time
snap7 120.00000	snapshot title & time
snap8 130.00000	snapshot title & time
snap9 140.00000	snapshot title & time
snap10 150.00000	snapshot title & time
snap11 160.00000	snapshot title & time
snap12 170.00000	snapshot title & time
snap13 180.00000	snapshot title & time
3	# of gages
gage1 800.0000 -27.00000 0.00000 180.00000	gage title, x, depth & times
gage2 1000.0000 -27.00000 0.00000 180.00000	gage title, x, depth & times
gage3 1205.0000 -8.00000 0.00000 180.00000	gage title, x, depth & times
11	# nodes in profile
0.00000 -30.00000	profile node
1000.00000 -30.00000	profile node
1005.00000 -29.93750	profile node
1010.00000 -29.75000	profile node
1015.00000 -29.43750	profile node
1020.00000 -29.00000	profile node
1180.00000 -11.00000	profile node
1185.00000 -10.56250	profile node
1190.00000 -10.25000	profile node
1195.00000 -10.06250	profile node
1200.00000 -10.00000	profile node
1	# wave components
4.00000 4.00000	height, period

Figure 4. Sample input file

³ The internal FORTRAN name is shown in Courier type at the end of each description, and the FORTRAN format specification is shown in parentheses at the end of the last line of each description.

line 1: A title for the computation which is reproduced as the first line of each output file, `title`. (a60)

line 2: The specification of the units: English units & SI units are supported. Only the first two letters are interpreted, English or En are equally acceptable (there is no abbreviation of SI). All subsequent input and output quantities are assumed to be in these units, `qunits`. (a2)

line 3: The specification of the type of shore side boundary: open or reflection. Only the first two letters are interpreted and therefore one can write op for open or re for reflection, `rhshbdy`. (a2)

line 4: The horizontal extent of the computational domain, `xmax`. (f10.5)

line 5: The maximum time, `tmax`. (f10.5)

line 6: The number of desired spatial snapshots of the variables (must be 20 or fewer specifications), `nsnap`. (i5)

next
 `nsnap`
 lines: Specifications for the snapshots (one snapshot specification per line). Each specification consists of:
 1. The title of the new file for the output, `tsnap`.
 2. The time at which the snapshot is to be taken, `tss`. (a10,f10.5)

next line: The number of desired wave gage time histories (must be 20 or fewer specifications), `ngage`. (i5)

next
 `ngage`
 lines: Specifications for the time histories (one time history per line). Each specification consists of:
 1. The title of the new file for the output, `tgage`.
 2. The x-location of the wave gage, `xgage`.
 3. The depth of the wave gage, `gagedp`.
 4. The starting time, `tsq1`.
 5. The ending time, `tsq2`. (a10,4f10.5)

next line: The number of nodes in the bottom polygon (must be 50 or fewer nodes), `nbottm`. (i5)

next
 `nbottm`
 lines: The coordinates of the next node of the bottom polygon. The first node must correspond to the location of the wave maker; the last node must correspond to the location where an open boundary condition is enforced (if used). (`xbottm`, `abottm`). (2f10.5)

next line: The number of wave components for the wave maker, `nwaves`. (i5)

If `nwaves` = 1, then

next line: The specifications of a regular wave:

1. wave height, height.
2. wave period, period.

(2f10.5)

If nwaves > 1, then

next The components of a random wave train (one line per component):

nwaves

lines:

1. wave amplitude, ampwav.
2. wave frequency, freqwv.
3. wave phase. If the phase of the wave is larger than 180°, then the phases will be replaced by random phases, phaswv. (3f10.5)

PART V: MODEL OUTPUT

There are three types of output files: an echo of the original data (written into the "output" file), snapshot files, and wave gage files.

The input, together with any error messages and a few derived quantities, such as the number of time steps and the number of spatial steps, is echoed to the computer screen. Since the information on the screen is volatile, this information (except for fatal error messages) is also saved in an output file for future reference. The purpose of this output file is to provide evidence that the input quantities were indeed read in correctly and to form a permanent record of the calculation.

The snapshot files have a header describing the computation, followed by a tabular list of values of the independent and dependent variables. These values are given for the whole computational domain, plus at the four points: $i = 1$, $i = 2$, $i = ns + 3$, and $i = ns + 4$. These latter points are outside the computational domain and are needed for restart. Figure 5 is a remnant of a snapshot file corresponding to the input file given above. (The numbers in this remnant were reduced by the least significant figure so that it can be printed on the page).

The header contains the title on the first line and the second line is blank. The third line contains the specified units and the fourth line the specified right-hand boundary condition. The fifth line is blank. The sixth line contains the exact time of the snapshot (which may be slightly different from that specified in the input file, as a result of the time discretization). The seventh line contains the time step index corresponding to the time and the eighth line contains dx , the spacing between nodes. The ninth, tenth, and eleventh lines are blank. The twelfth line contains a list of column titles and the remaining lines (beginning at the thirteenth line) are output data. The first two lines and last two lines of output data contain information on the points outside the computational domain. The column titles and the output data columns are separated by tabs so that the entire matrix can be easily pasted into a spread sheet or into popular graphing programs.

The meanings of the variables in the output files are:

location:

x The distance from the first point in the computational domain.

independent variables:

β The amplitude of the wave above the undisturbed free surface.
 u_0 The component of velocity which is constant in z .
 u_1 The component of velocity that varies linearly with z .

dependent variables:

- pbar** The pressure measured at the wave gage (at a z coordinate of **gagedp**).
- p0** The integrated pressure (integrated from the bottom to the actual water surface at this location).
- p1** The first moment of pressure (the pressure multiplied by z and integrated from the bottom to the actual water surface at this location).

All of these variables are expressed in units consistent with those given in the input specification. For instance, if English units are selected, **beta** is in feet, **u0** in feet/sec, **u1** in 1/sec, **pbar** in lb/ft², **p1** in lb/ft and **p1** in ft-lb/ft. Note that the meaning of the "/ft" in **p0** and **p1** is that these are the force and moment per foot of wave tank in and out of the paper (i.e., in the y or third dimension).

The wave gage files are time histories of the same variables displayed in the snapshot files. The user can specify in the input for each gage the times to start and stop the recording of the time series. Figure 6 shows a remnant of a wave gage file.

Collision Against Hydraulic Gate

English units

reflection boundary condition on rhs

x-gauge = 1200.6225
gauge depth = -8.0000
t-start = 0.0000
t-stop = 180.0000
dt = 0.0400

time	beta	u0	u1	pbar	p0	p1
0.40000E-01	0.18155E-35	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.80000E-01	0.11768E-34	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.12000E+00	0.43946E-34	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.16000E+00	0.12392E-33	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.20000E+00	0.29200E-33	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.24000E+00	0.60787E-33	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.28000E+00	0.11570E-32	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.32000E+00	0.20396E-32	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.36000E+00	0.34815E-32	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
0.40000E+00	0.56492E-32	0.00000E+00	0.00000E+00	0.51350E+03	0.32124E+04	-0.21426E+05
...						
0.17940E+03	-0.16006E+00	0.00000E+00	0.00000E+00	0.52889E+03	0.33627E+04	-0.22407E+05
0.17944E+03	-0.37376E+00	0.00000E+00	0.00000E+00	0.51450E+03	0.32167E+04	-0.21673E+05
0.17948E+03	-0.57628E+00	0.00000E+00	0.00000E+00	0.50063E+03	0.30793E+04	-0.20964E+05
0.17952E+03	-0.76750E+00	0.00000E+00	0.00000E+00	0.48737E+03	0.29507E+04	-0.20287E+05
0.17956E+03	-0.94745E+00	0.00000E+00	0.00000E+00	0.47478E+03	0.28310E+04	-0.19643E+05
0.17960E+03	-0.11163E+01	0.00000E+00	0.00000E+00	0.46289E+03	0.27202E+04	-0.19037E+05
0.17964E+03	-0.12742E+01	0.00000E+00	0.00000E+00	0.45171E+03	0.26179E+04	-0.18468E+05
0.17968E+03	-0.14215E+01	0.00000E+00	0.00000E+00	0.44125E+03	0.25239E+04	-0.17936E+05
0.17972E+03	-0.15959E+01	0.00000E+00	0.00000E+00	0.43149E+03	0.24375E+04	-0.17442E+05
0.17976E+03	-0.16858E+01	0.00000E+00	0.00000E+00	0.42241E+03	0.23585E+04	-0.16984E+05
0.17980E+03	-0.18038E+01	0.00000E+00	0.00000E+00	0.41399E+03	0.22862E+04	-0.16560E+05
0.17984E+03	-0.19129E+01	0.00000E+00	0.00000E+00	0.40621E+03	0.22204E+04	-0.16170E+05
0.17988E+03	-0.20137E+01	0.00000E+00	0.00000E+00	0.39905E+03	0.21606E+04	-0.15812E+05
0.17992E+03	-0.21066E+01	0.00000E+00	0.00000E+00	0.39248E+03	0.21063E+04	-0.15485E+05
0.17996E+03	-0.21920E+01	0.00000E+00	0.00000E+00	0.38647E+03	0.20573E+04	-0.15188E+05
0.18000E+03	-0.22705E+01	0.00000E+00	0.00000E+00	0.38098E+03	0.20131E+04	-0.14917E+05

Figure 5. Typical snapshot file

Collision Against Hydraulic Gate

English units

reflection boundary condition on rhs

t-snapshot = 130.0000

time step = 3250

dx = 0.8031

x	beta	u0	u1	pbar	p0	p1
-0.1606184E+01	-0.2507322E+00	-0.1904417E+00	-0.6757135E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00
-0.8030920E+00	-0.1285472E+00	-0.3415523E-01	-0.1978589E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1859984E+00	0.8427900E-01	0.1308408E-02	0.2800753E+04	0.4839667E+05	-0.9287255E+06
0.8030920E+00	0.3288133E+00	0.2279711E+00	0.5856389E-02	0.1939012E+04	0.2936335E+05	-0.5842389E+06
0.1606184E+01	0.4406113E+00	0.3831724E+00	0.1102049E-01	0.1940047E+04	0.2945186E+05	-0.5850902E+06
0.2409276E+01	0.5478837E+00	0.5401618E+00	0.1631687E-01	0.1941205E+04	0.2954645E+05	-0.5860394E+06
0.3212368E+01	0.6727371E+00	0.6923208E+00	0.2143332E-01	0.1942872E+04	0.2965071E+05	-0.5871218E+06
0.4015460E+01	0.8023650E+00	0.8406266E+00	0.2642880E-01	0.1944606E+04	0.2975196E+05	-0.5881588E+06
0.4818552E+01	0.9356932E+00	0.9856594E+00	0.3133948E-01	0.1946370E+04	0.2985186E+05	-0.5891699E+06
0.5621644E+01	0.1061951E+01	0.1128877E+01	0.3624144E-01	0.1948003E+04	0.2994777E+05	-0.5901272E+06
0.6424736E+01	0.1185373E+01	0.1268727E+01	0.4106191E-01	0.1949571E+04	0.3004087E+05	-0.5910479E+06
. . .						
0.1189379E+04	0.1010221E+01	-0.6618290E+00	-0.3934373E-01	0.6888285E+03	0.3852133E+04	-0.2518796E+05
0.1190182E+04	0.1352003E+01	-0.6378232E+00	-0.4059707E-01	0.6962896E+03	0.3970417E+04	-0.2545099E+05
0.1190985E+04	0.1717653E+01	-0.6070414E+00	-0.4113132E-01	0.7036911E+03	0.4094860E+04	-0.2572924E+05
0.1191788E+04	0.2106759E+01	-0.5699427E+00	-0.4096023E-01	0.7112735E+03	0.4224531E+04	-0.2600544E+05
0.1192592E+04	0.2533191E+01	-0.5313188E+00	-0.4158284E-01	0.7176491E+03	0.4349106E+04	-0.2620096E+05
0.1193395E+04	0.2988911E+01	-0.4815454E+00	-0.4007342E-01	0.7248405E+03	0.4480725E+04	-0.2639659E+05
0.1194198E+04	0.3478565E+01	-0.4285489E+00	-0.3900182E-01	0.7301403E+03	0.4597841E+04	-0.2647372E+05
0.1195001E+04	0.3993726E+01	-0.3636527E+00	-0.3490562E-01	0.7359553E+03	0.4717891E+04	-0.2655559E+05
0.1195804E+04	0.4533112E+01	-0.2941036E+00	-0.2944273E-01	0.7412966E+03	0.4833339E+04	-0.2663207E+05
0.1196607E+04	0.5078669E+01	-0.2264461E+00	-0.2389306E-01	0.7458793E+03	0.4937572E+04	-0.2667076E+05
0.1197410E+04	0.5606828E+01	-0.1609669E+00	-0.1785218E-01	0.7495759E+03	0.5026451E+04	-0.2667076E+05
0.1198213E+04	0.6053394E+01	-0.1018092E+00	-0.1174038E-01	0.7520964E+03	0.5092758E+04	-0.2663021E+05
0.1199016E+04	0.6363204E+01	-0.4854281E-01	-0.5804313E-02	0.7533824E+03	0.5132183E+04	-0.2656747E+05
0.1199819E+04	0.6478028E+01	0.0000000E+00	0.0000000E+00	0.9061471E+03	0.6935873E+04	-0.3293404E+05
0.1200623E+04	0.6363198E+01	0.4856327E-01	0.5804432E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.1201426E+04	0.6053391E+01	0.1018544E+00	0.1174141E-01	0.0000000E+00	0.0000000E+00	0.0000000E+00

Figure 6. Typical wave gage file

PART VI: PROGRAM USAGE

The actual usage of the program is quite simple. Upon startup, the user is prompted for two pieces of information: the name of the input file and the name of the output file (for the echo of the input data). The program does not assume a fixed name for these two files, so the user can choose input and output file names that are descriptive of the particular wave situation that these files represent. All of the rest of the input information is contained in the referenced input file. The program reads the data in the input file, performs several initialization steps, and then echoes the data to the screen and output file.

Restart

After the input file is read the program asks: Is this a restart? (y/n). If the user has completed a calculation and wishes either to have more snapshots around a critical event, to have more wave gages or to extend the previous computation, the answer should be: y; if this is the first calculation with this geometry, the answer should be: n.

If the answer is y, the user will be prompted with: restart file name = ?. The user is to input the name of the snapshot file corresponding to the beginning time of the new computation. Each snapshot file captures the "state" of the flow and therefore contains enough information for restart. The input file elements that result in output quantities can be different for the rerun from those which were in the original input file. These are:

	line 1,	the title of the computation.
	line 5,	the maximum time.
	line 6,	the number of desired spatial snapshots.
next nsnap	lines,	the snapshot specifications.
next	line,	the number of desired wave gage time histories.
next ngage	lines,	the snapshot specifications.

All other lines in the input must be the same as the calculation that produced the referenced snapshot file for the program to run correctly.

The ability to rerun the computation is a powerful tool that allows the user to refine the information he wishes to obtain from the program.

Run Time

The time for execution of the program is proportional to the product of two numbers: the number of spatial nodes and the number of time steps. The program displays these two numbers on the screen during the echo of the "input" and records them in the "output" file. The time required will depend, of course, on the particular computer used to perform the calculations. It is suggested that the user perform a computation and determine the

"calibration factor" for his own system.

Because some large problems may take hours to run, the iteration number is printed out at the beginning of each time step. This assures the operator that the calculation is proceeding normally. Further, an annotation on the screen is made each time a snapshot file is written.

Run time for the model varies depending on type of simulation performed (regular versus random waves), on the desired size of the modeling domain, and on the computer platform used to run the program. On Cray YM-P computer, the run time for a pseudo-random wave of 20 components (i.e. spectral wave simulation) was less than four hours for a region extending 10 miles in on-offshore direction. For a single component wave (i.e., regular wave), the simulation time for a 4 miles stretch was 23 minutes on a 386/33 MHz PC and 7.4 minutes on a VAX 8800 series mainframe computer.

REFERENCES

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Shields, J. J. 1986. "A Direct Theory for Waves Approaching a Beach," Ph.D. thesis, University of California at Berkeley, p. 137.

Shields, J. J., and Webster, W. C. 1988. "On Direct Methods in Water-Wave Theory," J. Fluid Mech., Vol 197, pp. 171-199.

APPENDIX A: EXAMPLES

Example I: Reflection of Waves from a Spillway Hydraulic Gate

A schematic (with the vertical scale exaggerated) of the geometry of a body of water downstream of a hydraulic structure (say, a sluice gate) is shown in Figure A1. The water depth is 30 ft downstream and a smooth transition is provided in the 200 ft in front of the sluice gate to a water depth of 10 ft (at the sluice gate). GNWave was run to simulate the situation where 4-ft-high waves of 4-sec period progress from the deepwater region up to the gate and are reflected by the gate. Engineering questions for this situation include:

- How high will the waves be at the sluice gate?
- What forces will be exerted on it?
- Where is the center of pressure of these forces?

The computational domain selected is 1,200 ft in length (as shown in Figure A2). This provides for a large number of waves in the numerical tank and allows for a long period of simulated time to transpire before the waves reflected by the sluice gate impact the wave maker. The waves in the deep part of the tank are relatively short (about 80 ft) and therefore behave more like deepwater waves. These same waves near the sluice gate (where the water depth is only 10 ft) behave like shallow-water waves. The input file is shown as Figure 4 in the main body of this report.

Results and Discussion

Figures A2 through A4 show snapshots of the water surface at 10-sec intervals. Several features are apparent. Before the wave train reaches the sluice gate, the leading wave is noticeably higher than those which follow. This is a direct result of the dispersive character of these finite water depth waves (Mei 1989).¹ When this large wave impacts the sluice gate, it produces larger waves (over 10 ft in height) there as well. This wave is reflected, the subsequent waves in the train result in waves which average 8 ft in height and whose envelope appears to oscillate over a period of about five waves. The snapshot at $t = 180$ clearly shows that the reflected waves are beginning to impinge on the wave maker. Further, an examination of the wave closest to the sluice gate shows the beginning of an instability resulting from this impingement. Thus, continuation of the simulation is suspect. We should note that a similar situation would be encountered in a physical wave tank of limited size.

Figure A5 shows the time history of the wave amplitude at the three gage locations $x = 800$ ft, $x = 1,000$ ft and $x = 1,200$ ft (i.e., at the sluice gate). The effect of the wave reflection is to form standing waves, which can be clearly seen by comparison of the three gages. In particular, gage 2 is very nearly at a node. Figure A6 shows the time history of the pressure measured by pressure gages placed 2 ft above the bottom. This history resembles the wave elevation time history, but frequency doubling can be seen when standing waves are formed.

¹ See References at the end of the main text.

Figure A7 shows the history of the total force per foot of sluice gate (the variable p_o in Demirbilek and Webster (1992)) and the location of the center of pressure (the ratio p_1/p_o , Demirbilek and Webster (1992)). Wave reflection by a sluice gate produces large standing waves in the neighborhood of the gate and large oscillatory forces on the gate.

The effect of the sloping seabed at the toe of the structure, which may also be treated as a substantial berm in front of the sluice gate, can readily be studied with the model GNWave. For instance, wave results may be produced for varying slopes to discern slope effects in design estimates, including estimating wave forces. It may not be possible to estimate such effects from the results of a single run.

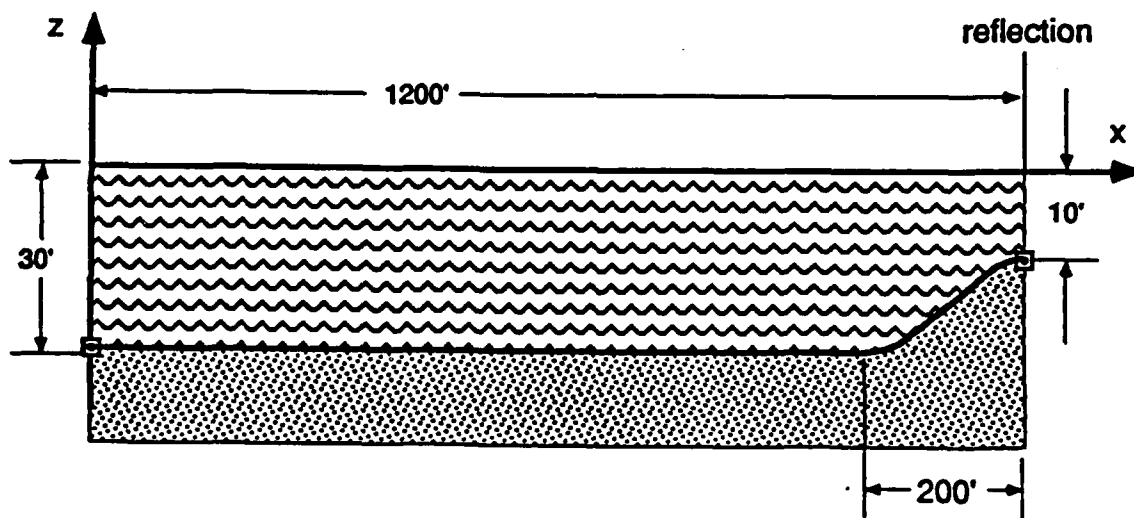


Figure A1. Configuration for the test of wave collision with a sluice gate

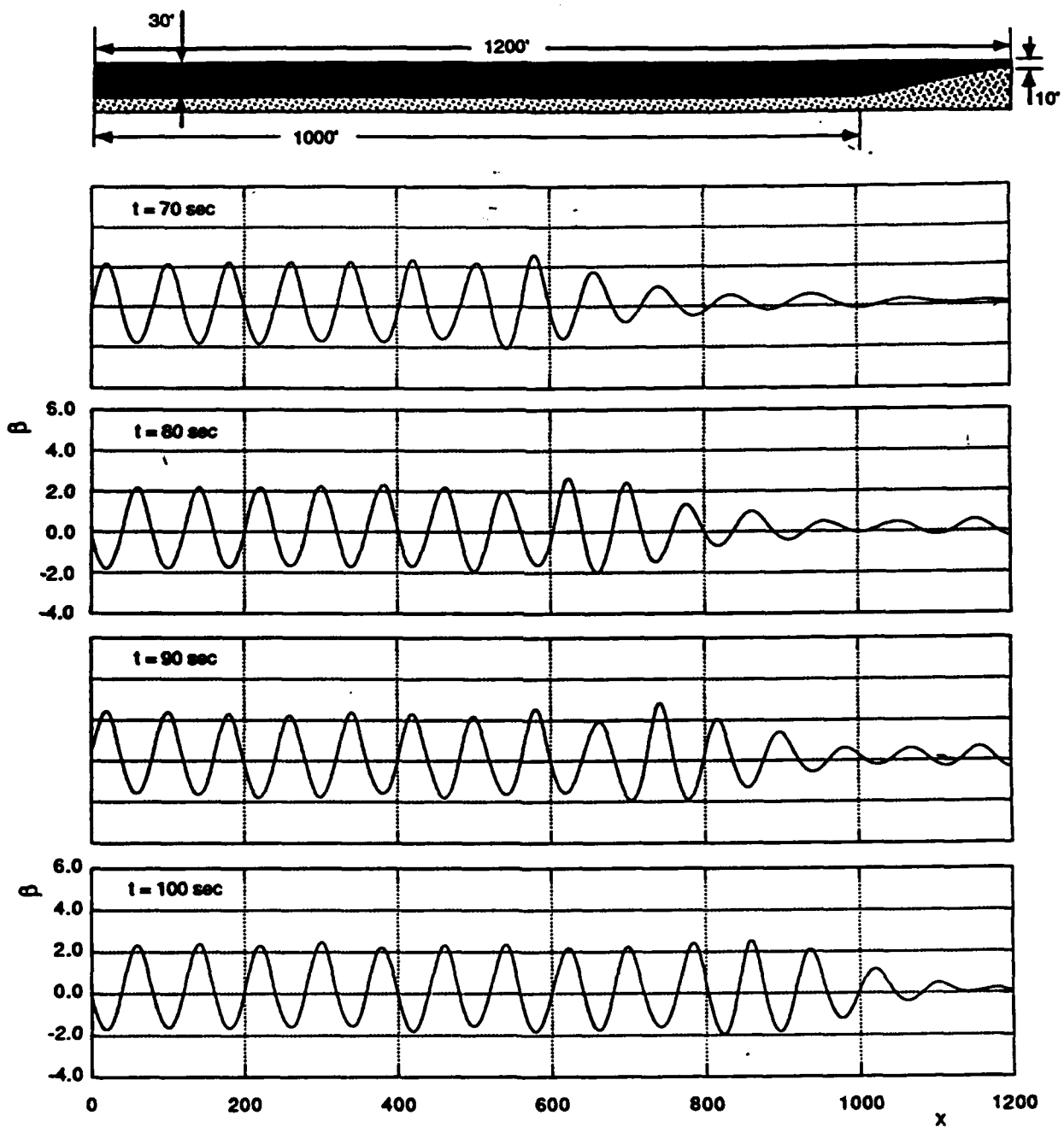


Figure A2. Waves approaching sluice gate (shown at 10-sec intervals)

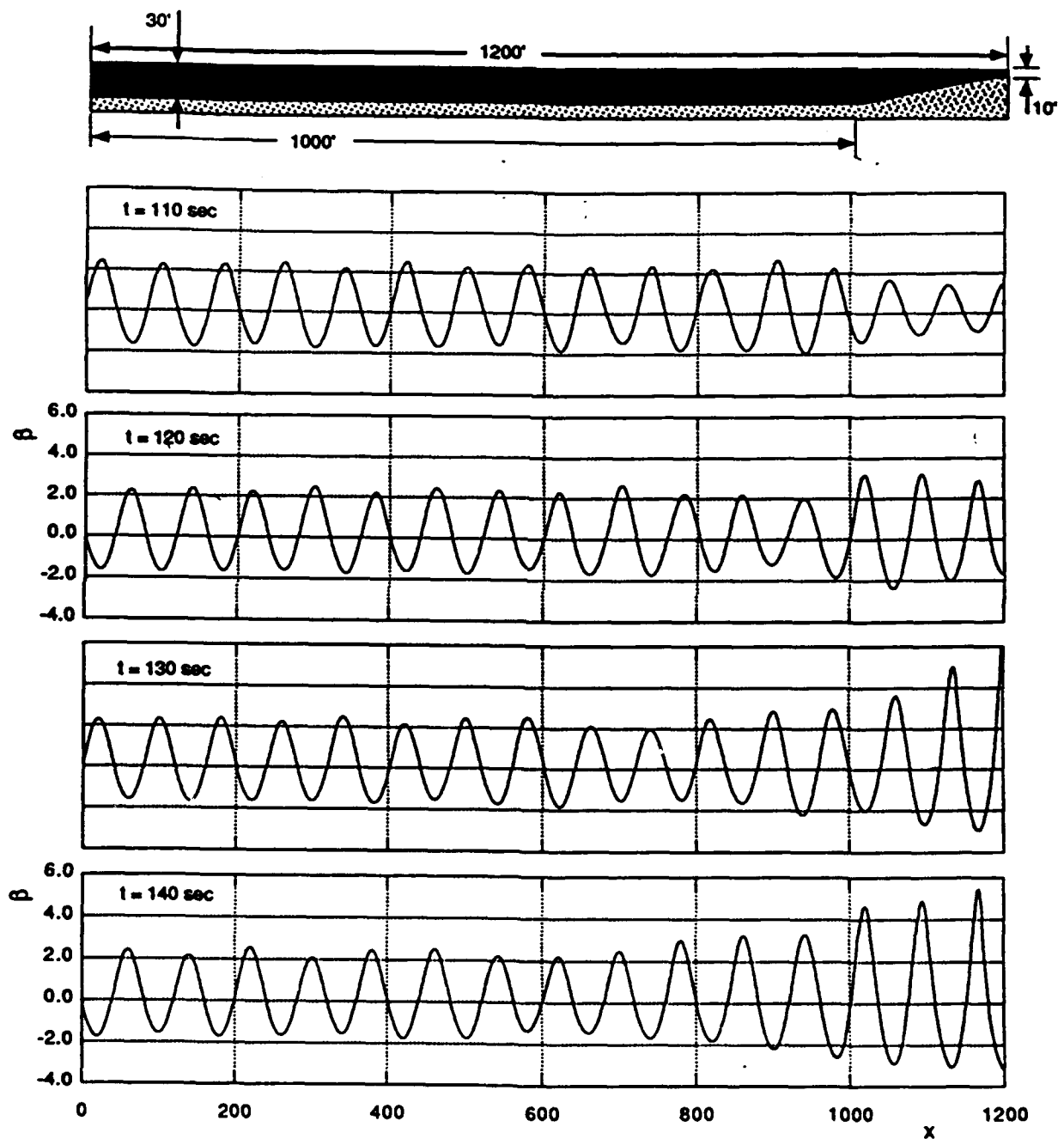


Figure A3. Waves approaching sluice gate (shown at 10-sec intervals)

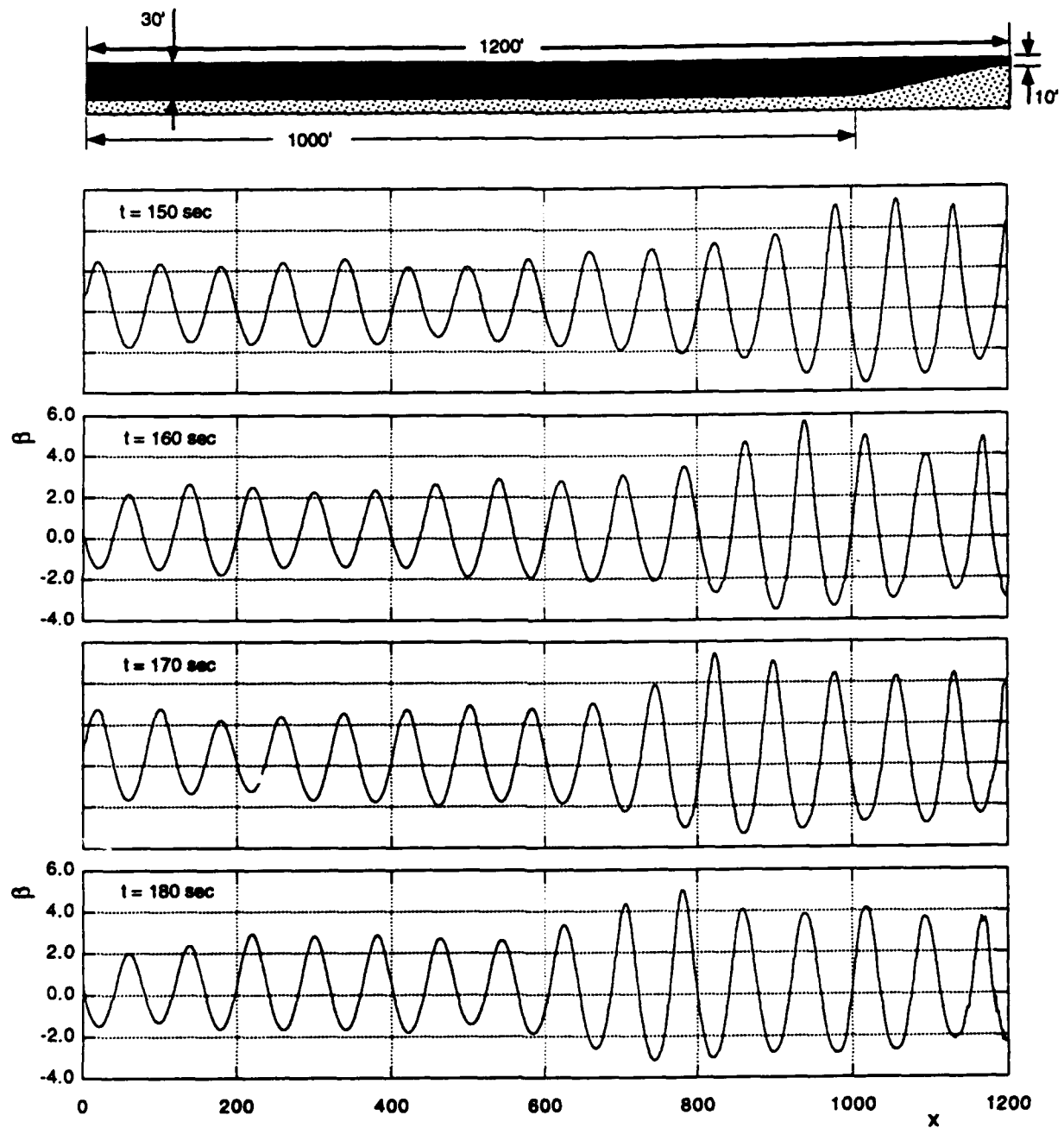


Figure A4. Waves approaching sluice gate (shown at 10-sec intervals)

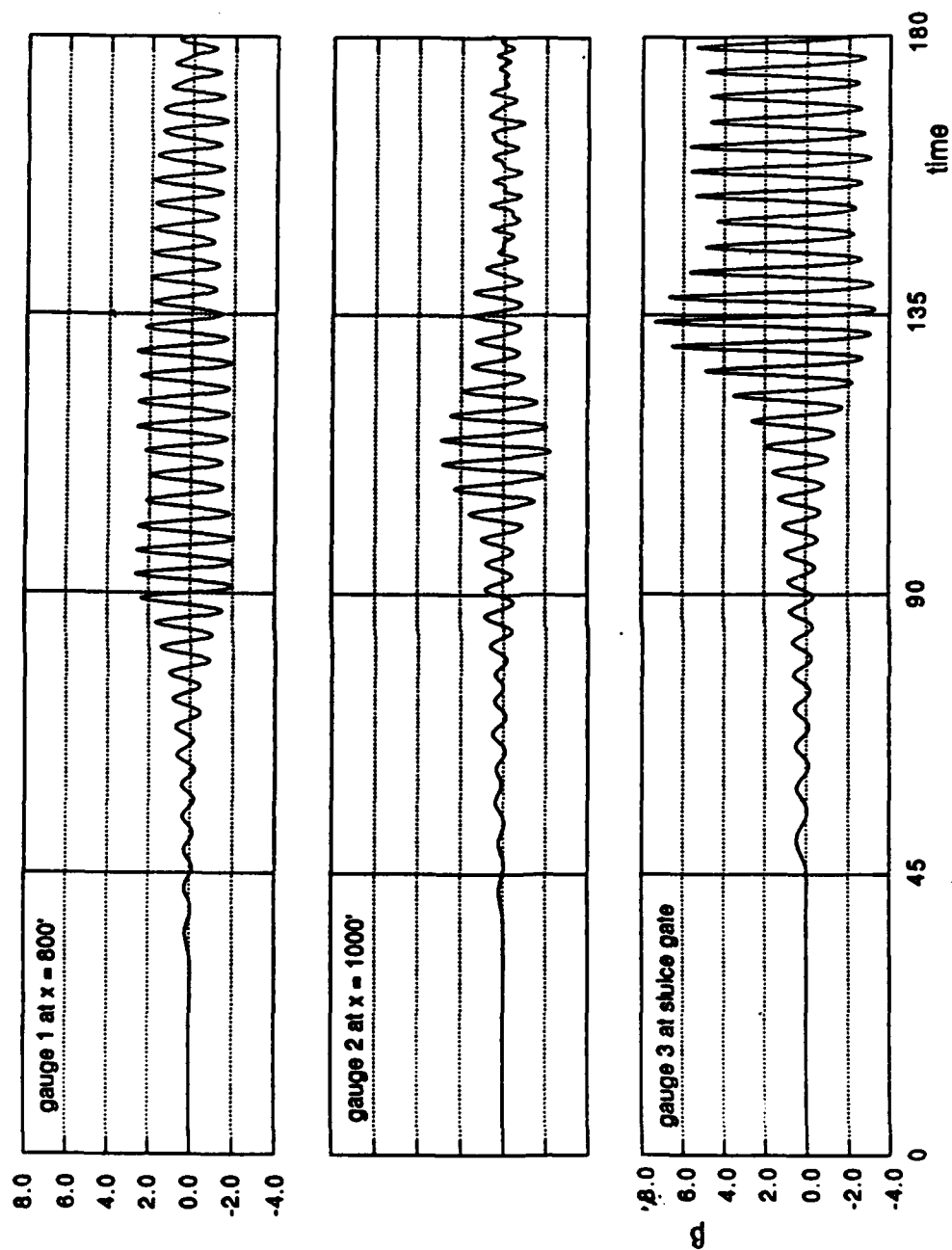


Figure A5. Wave elevation measured at three gage locations

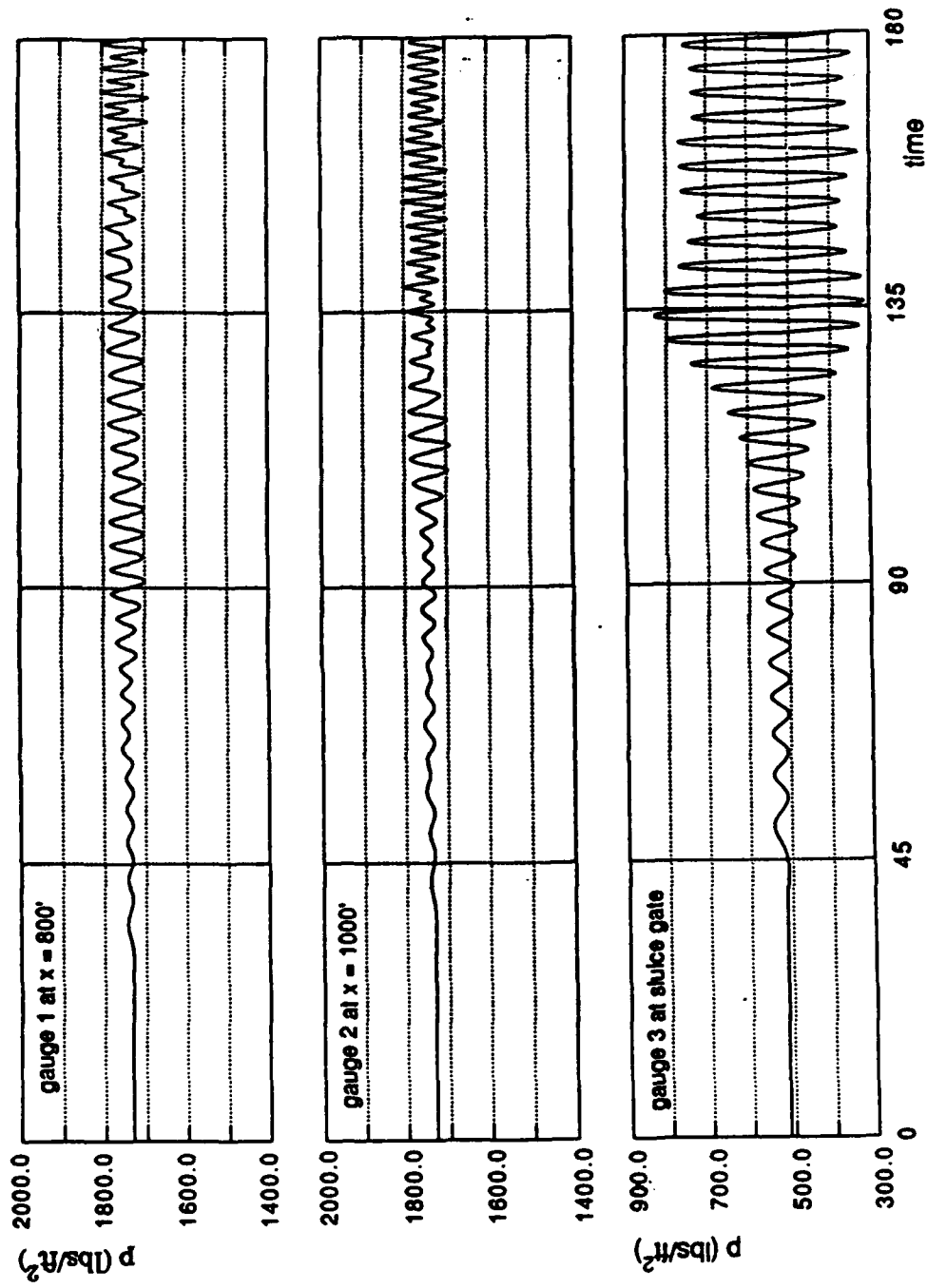


Figure A6. Pressure measured 2 ft off bottom at three gage locations

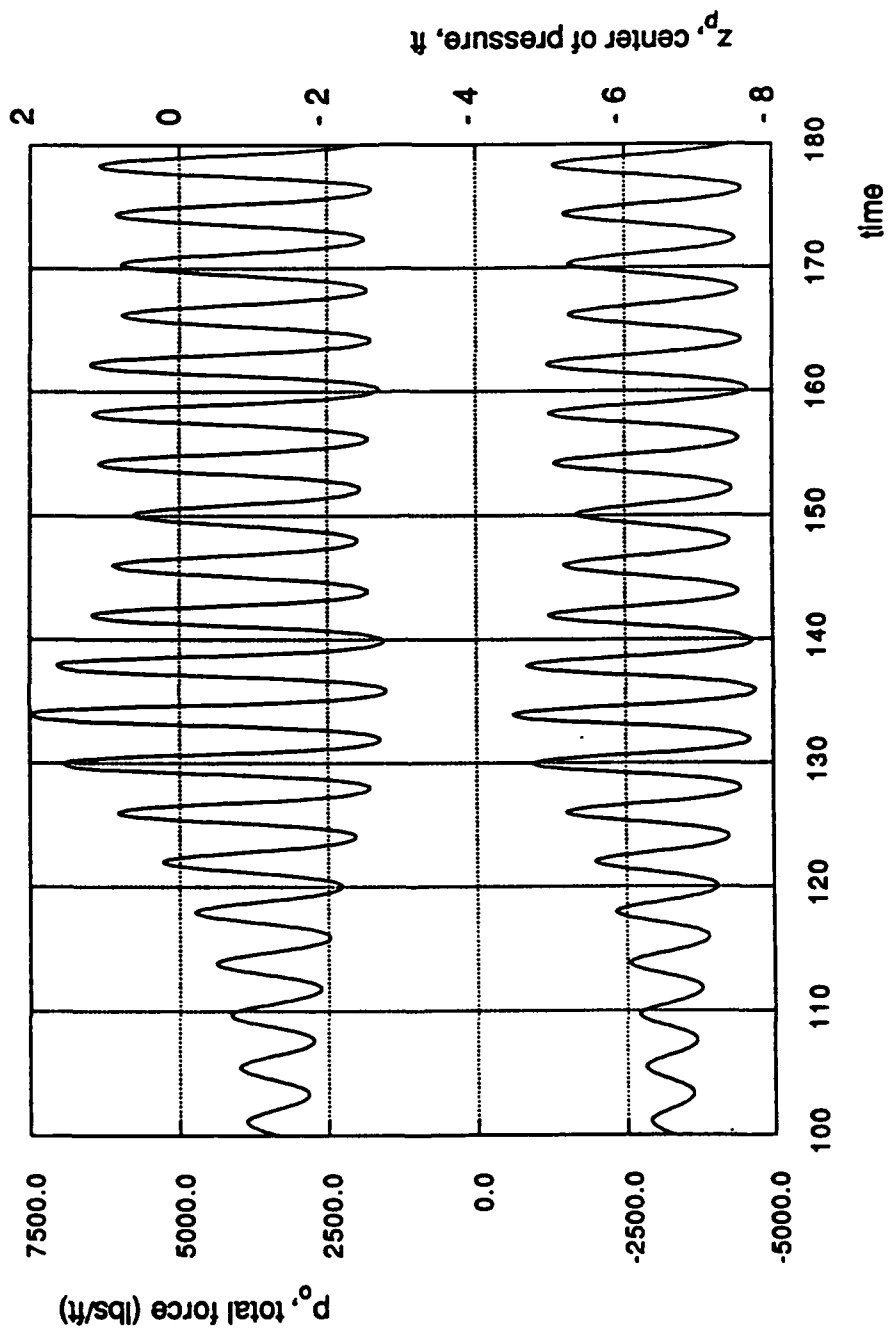


Figure A7. Force and center of pressure time history at the sluice gate

Example II: Wave Transformation over an Open-ended Sloping Beach

The implementation of an open boundary condition (a condition that allows the free passage of waves) is a matter of some experimentation, since there is no exact theoretical statement for this condition. The program GNWave implements a Schrödinger condition in which the celerity of the wave is assumed known. For most situations this boundary condition is adequate, although it can be expected to fail eventually.

For this test of the open boundary condition, the short numerical wave tank is 200 ft long and a straight sloped bottom is chosen (see Figures A8 and A9). Waves of 5-sec period and 4 ft in height are generated at the left-hand side. These waves are about 120 ft long and, therefore, quickly fill the tank. The computation was allowed to proceed for 50 sec, corresponding to the creation of 10 waves. A single wave gage was placed at $x = 100$ ft, the center of the tank. The input file is:

Test of open boundary condition	Title
English	units (En or SI)
open	rhs b.c. (op or re)
200.00000	x-domain
50.00000	t-domain
5	# of snapshots
snap1 10.00000	snapshot title & time
snap2 20.00000	snapshot title & time
snap3 30.00000	snapshot title & time
snap4 40.00000	snapshot title & time
snap5 50.00000	snapshot title & time
1	# of gages
gage1 100.00000 -30.00000 0.00000 50.00000	gage title, x, depth & times
2	# nodes in profile
0.00000 -30.00000	profile node
200.00000 -15.00000	profile node
1	# wave components
4.00000 5.00000	height, period

Figure A8. Input for test of the open-boundary condition

Results and Discussion

The time history of the surface elevation at the wave gage is shown in Figure A10. The first few waves passing the gage were somewhat different in amplitude from the waves which are ultimately achieved in steady state. Figure A11 shows five snapshots at intervals of 10 sec. Since the wave period is 5 sec, these snapshots should be identical when steady state is achieved. The first snapshot is considerably different from the others because the first wave has not made it to the boundary.

The differences between the remaining snapshots are more difficult to discern, but the

differences can be most clearly seen at the right-hand edge of the domain. The difference between the snapshot at 40 sec and that at 50 sec is less than a line width. These waves have sharper crests than troughs due to nonlinear effects.

The shortening of the wave in the shallower water at the right-hand side of the domain is also obvious in these snapshots. The open boundary condition appears to work satisfactorily and permits over 10 waves of moderate steepness to pass through the boundary with no visible reflections or distortions.

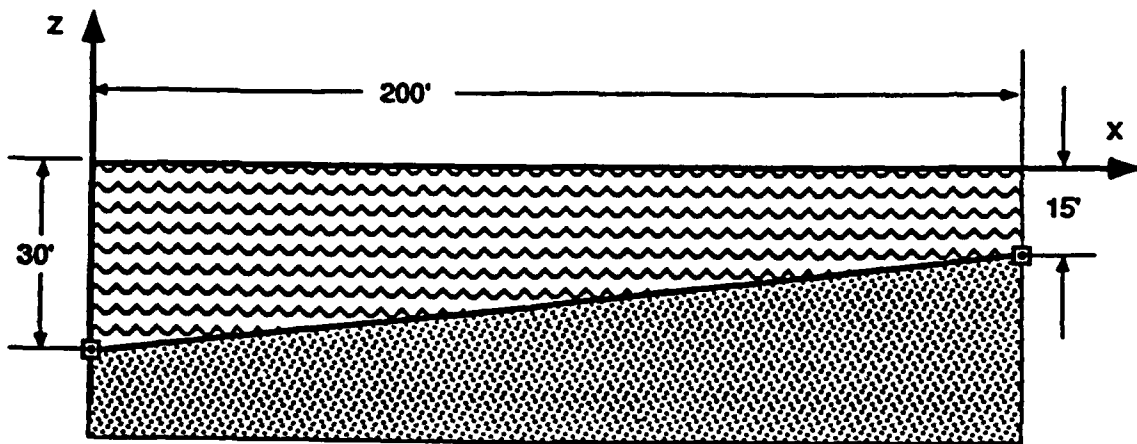


Figure A9. Configuration for test of open boundary condition

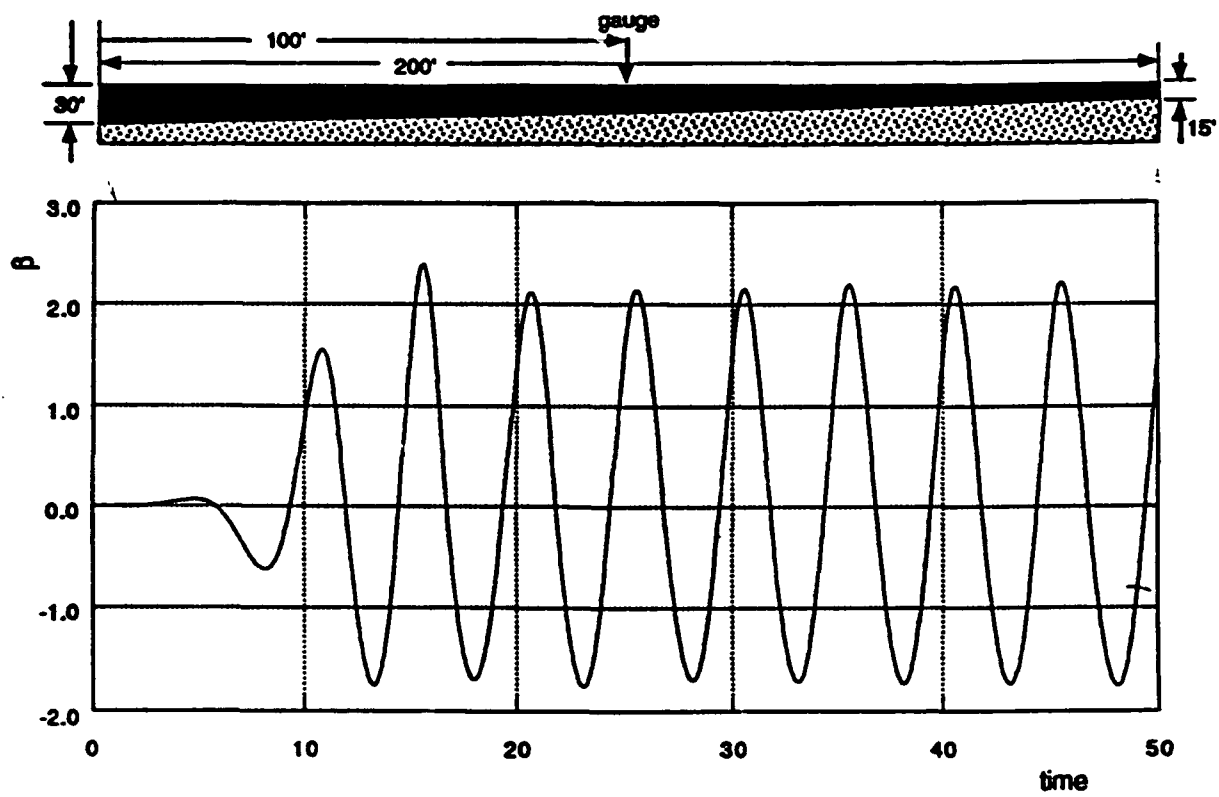


Figure A10. Time history of water elevation at gage 1

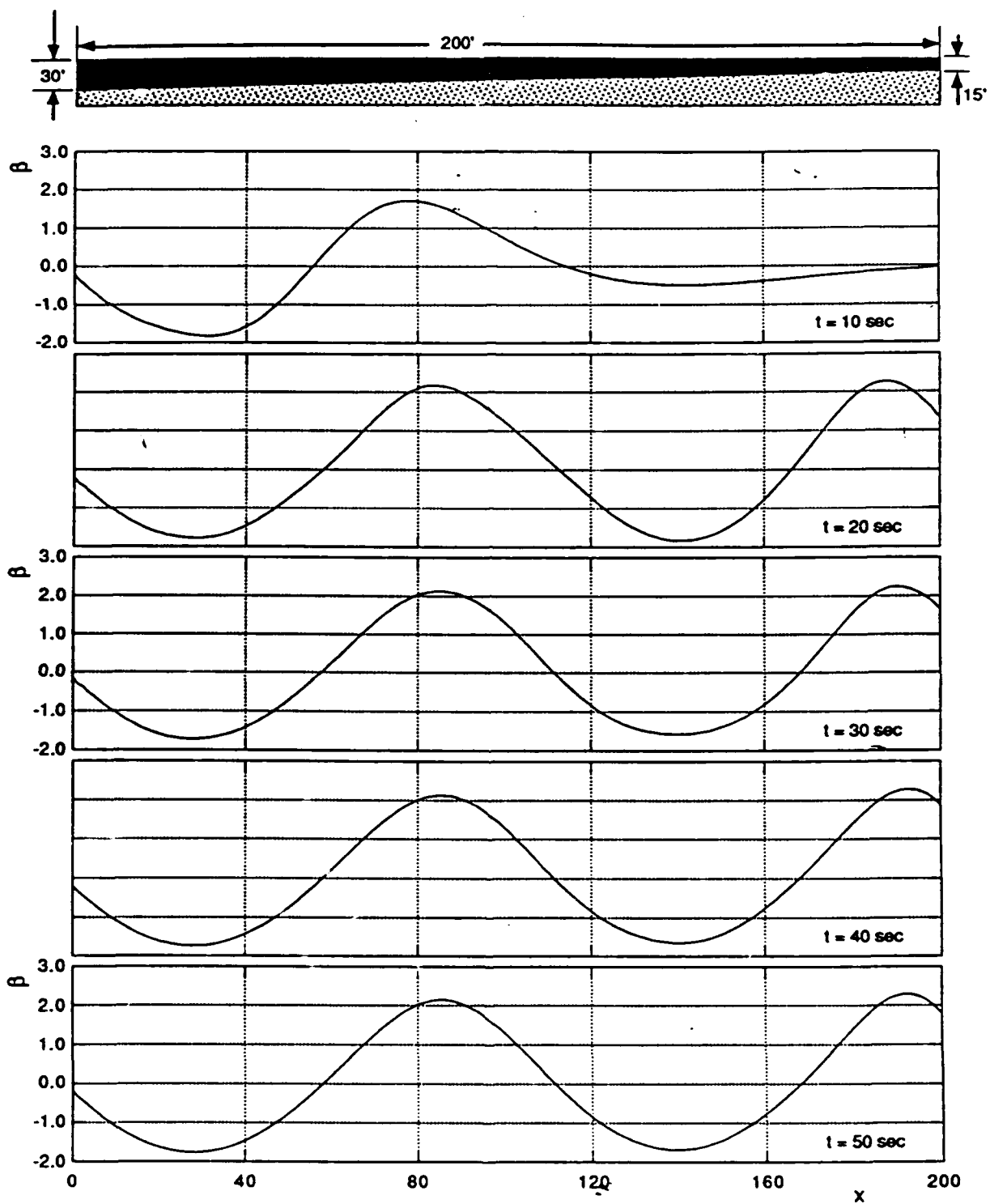


Figure A11. Wave profiles for successive 10-sec intervals

Example III: A Spectral Wave over a Sandbar and through a Navigational Channel

When finite waves pass over a submerged disturbance, such as a sandbar, they steepen. If the sandbar is not too pronounced, these steep waves will not break. When they pass the sandbar, the waves once again decrease in amplitude. An interesting question is: are these resulting waves substantially different in character from the waves before the sandbar? If the waves were small enough so that linear wave theory applies (both in the neighborhood of the sandbar and elsewhere) then the answer is clearly that there is no remnant of the sandbar except for a change of phase of the wave corresponding to the slower phase speed of the wave in the neighborhood of the bar. In the case of waves steep enough to exhibit nonlinearities, the authors know of no literature, experimental or otherwise, which describes the situation. The case of interaction of multiple wave components in this situation is even more complicated.

In this worked example a pseudo-random wave train is allowed to evolve over two different bottom topographies: the first is water of uniform depth (in this case, a 10-ft depth), and the second is water that is 10 ft in depth everywhere except for a "sandbar." Each numerical wave tank is 800 ft long and an open boundary condition is applied on the right-hand boundary. The sandbar begins at a distance of 425 ft from the wave maker and extends for 150 ft downstream. The sandbar is therefore centered about a point 500 ft from the wave maker. The shape of the sandbar is a trapezoid with a flat top 50 ft in length. The pseudo random wave train is composed of five waves each, with an amplitude of 0.5 ft and each with a different frequency. Sketches of these two situations are shown in each of the following graphs.

Wave gages for each situation are placed at 250, 500, and 750 ft from the wave maker. For the case of the sandbar, these gages correspond to a point well upstream of the sandbar, right over the middle of the sandbar, and well downstream of the sandbar. The two input files are given below in Figures A12 and A13.

Test of Random Waves in a Channel

English

open

800.00000

135.00000

14

snap0 30.00000

snap1 40.00000

snap2 80.00000

snap2a 85.00000

snap2b 90.00000

snap2c 95.00000

snap2d 100.00000

snap2e 105.00000

snap2f 110.00000

snap2g 115.00000

snap3 120.00000

snap3a 125.00000

snap3b 130.00000

snap3c 135.00000

3

gage1 250.00000 -10.00000 0.00000 200.00000

gage2 500.00000 -10.00000 0.00000 200.00000

gage3 750.00000 -10.00000 0.00000 200.00000

2

0.00000 -10.00000

800.00000 -10.00000

5

0.50000 1.00000 200.00000

0.50000 1.21000 200.00000

0.50000 1.33000 200.00000

0.50000 1.41000 200.00000

0.50000 1.59000 200.00000

Title

units (En or SI)

rhs b.c. (op or re)

x-domain

t-domain

of snapshots

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

of gages

gage title, x, depth & times

gage title, x, depth & times

gage title, x, depth & times

nodes in profile

profile node

profile node

wave components

amplitude, freq & phase

amplitude, freq & phase

amplitude, freq & phase

amplitude, freq & phase

amplitude, freq & phase

Figure A12. Input for pseudo-random waves in a uniform depth channel

Test of Random Waves over a Sandbar

English

open

800.00000

135.00000

14

snap0 30.00000

snap1 40.00000

snap2 80.00000

snap2a 85.00000

snap2b 90.00000

snap2c 95.00000

snap2d 100.00000

snap2e 105.00000

snap2f 110.00000

snap2g 115.00000

snap3 120.00000

snap3a 125.00000

snap3b 130.00000

snap3c 135.00000

3

gage1 250.00000 -10.00000 0.00000 200.000

gage2 500.00000 - 6.00000 0.00000 200.000

gage3 750.00000 -10.00000 0.00000 200.000

6

0.00000 -10.00000

425.00000 -10.00000

475.00000 - 6.00000

525.00000 - 6.00000

575.00000 -10.00000

800.00000 -10.00000

5

0.50000 1.00000 200.00000

0.50000 1.21000 200.00000

0.50000 1.33000 200.00000

0.50000 1.41000 200.00000

0.50000 1.59000 200.00000

Title

units (En or SI)

rhs b.c. (op or re)

x-domain

t-domain

of snapshots

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

snapshot title & time

of gages

gage title, x, depth & times

gage title, x, depth & times

gage title, x, depth & times

nodes in profile

profile node

profile node

profile node

profile node

profile node

profile node

wave components

amplitude, freq & phase

amplitude, freq & phase

amplitude, freq & phase

amplitude, freq & phase

amplitude, freq & phase

Figure A13. Input for pseudo-random waves over a sandbar

Results and Discussion

Two problems of practical interest are considered in this example and simulation results for both are jointly displayed and compared to illustrate the effects of a sandbar on the down-wave propagating past the seabed mound.

Figures A13 through A19 show the profiles of the wave trains at various times in the interval from 0 - 135 sec. These figures are arranged so that the top two graphs are the waves in the channel and the bottom two are waves over a sandbar (a little sketch is placed on the graphs to differentiate the two). From these graphs, it is clear that the sandbar has a dramatic effect, especially on the waves that were initially steeper. It is also clear that whereas the waves upstream of the sandbar are nearly identical, those downstream are quite different in character.

Figures A20 through A22 show the time histories of the three wave gages for the two situations. It can be clearly seen that the waves upstream of the sandbar are identical. Those over the sandbar demonstrate the sharp, peaked character of waves in shoaling situations. Most interesting are the waves downstream of the sandbar (Figure A21). These waves are clearly much different in nature from the corresponding waves in the uniform depth channel. The peaked character of the near breaking waves near the sandbar is retained, resulting in a wave train which has more high-frequency content than those in the channel.

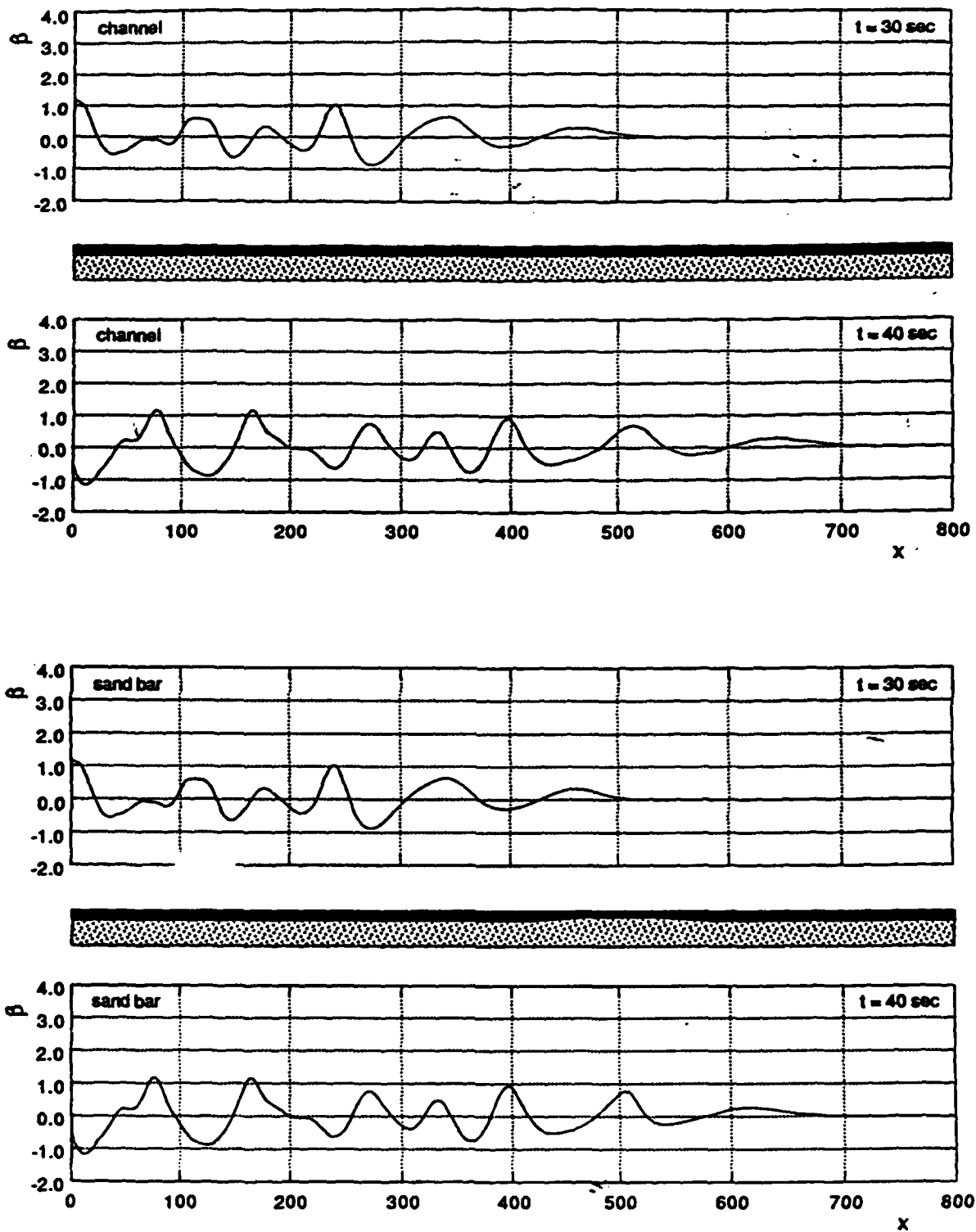


Figure A14. Snapshots of wave profiles at $t = 30$ sec and $t = 40$ sec

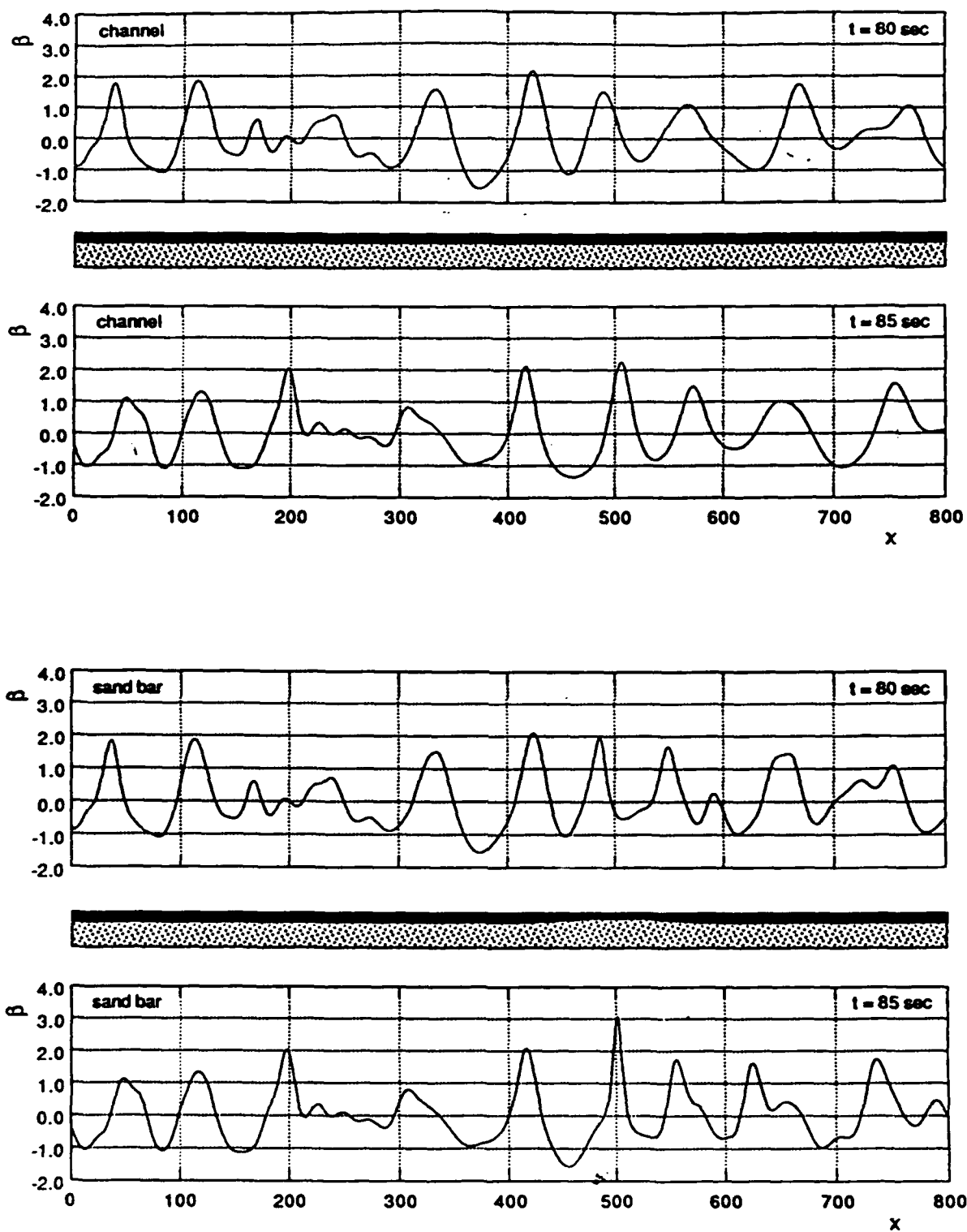


Figure A15. Snapshots of wave profiles at $t = 80$ sec and $t = 85$ sec

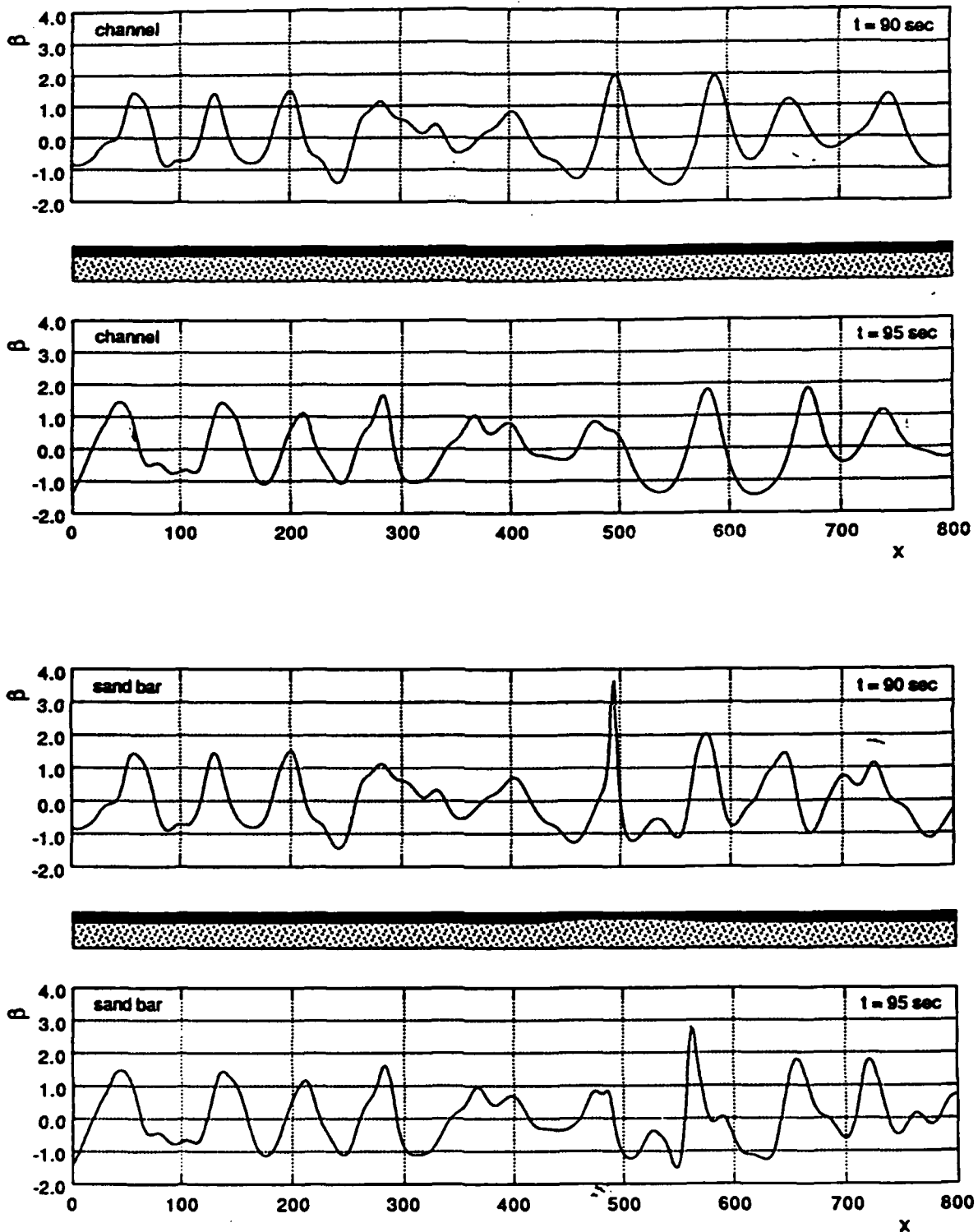


Figure A16. Snapshots of wave profiles at $t = 90$ sec and $t = 95$ sec

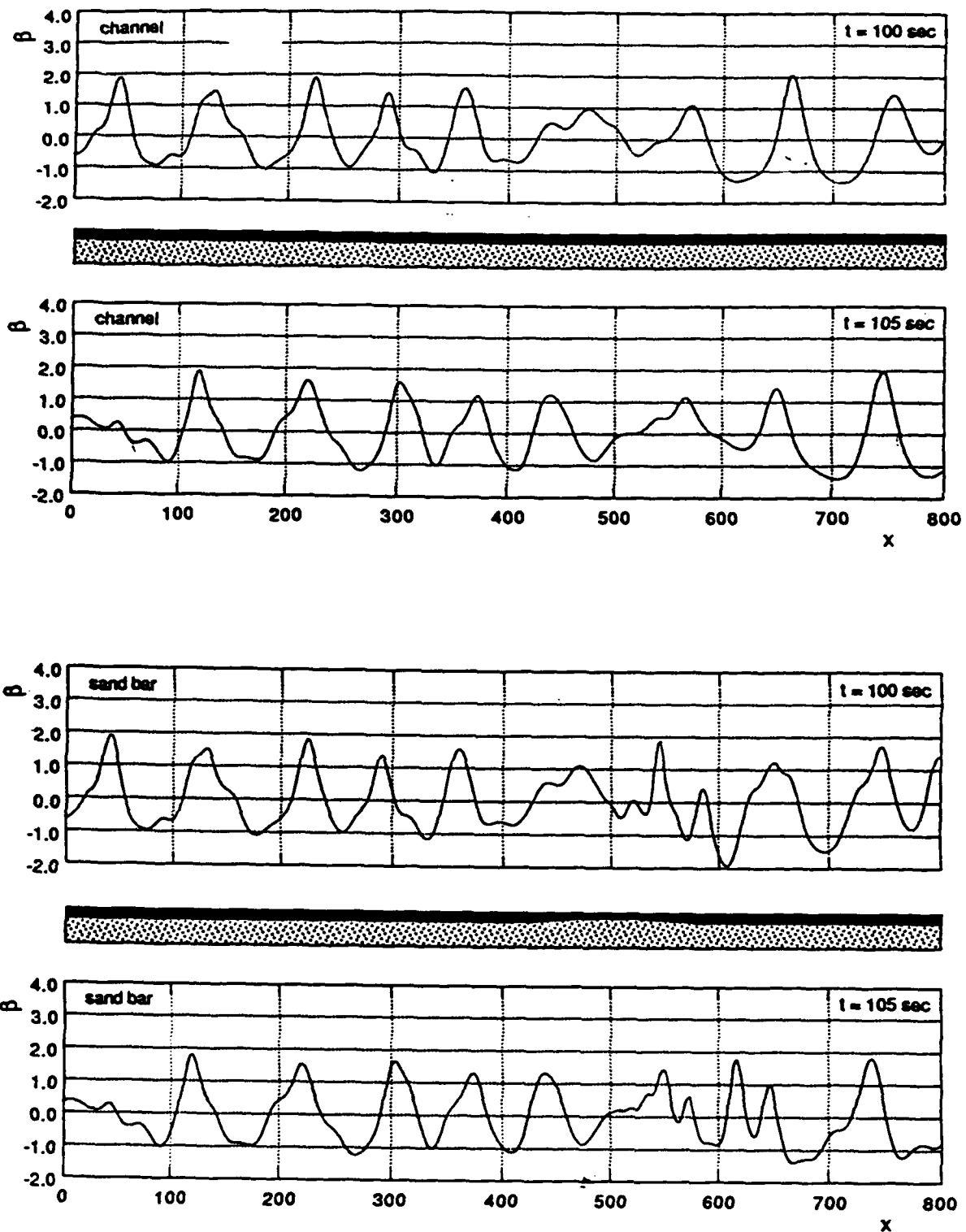


Figure A17. Snapshots of wave profiles at $t = 100$ sec and $t = 105$ sec

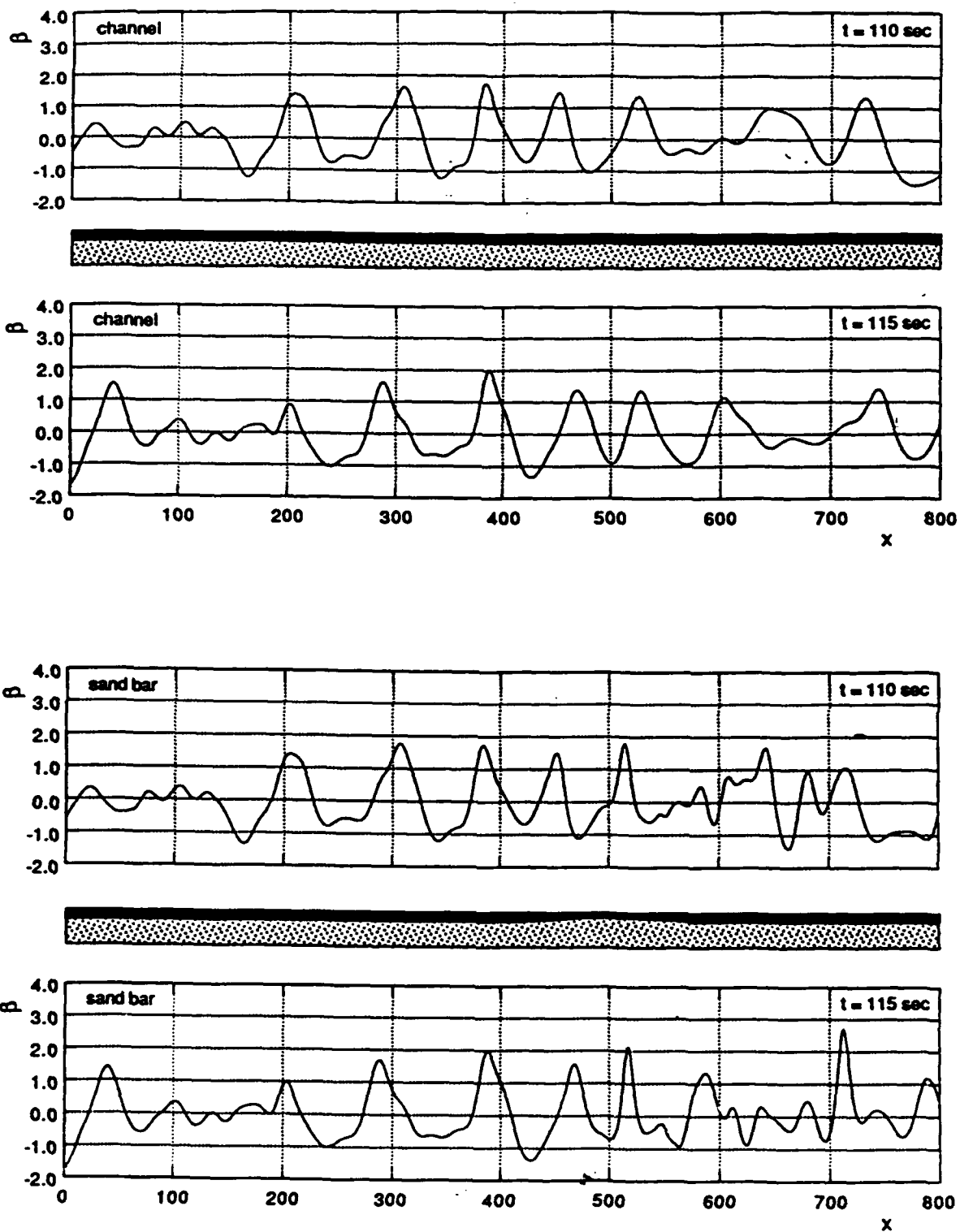


Figure A18. Snapshots of wave profiles at $t = 110$ sec and $t = 115$ sec

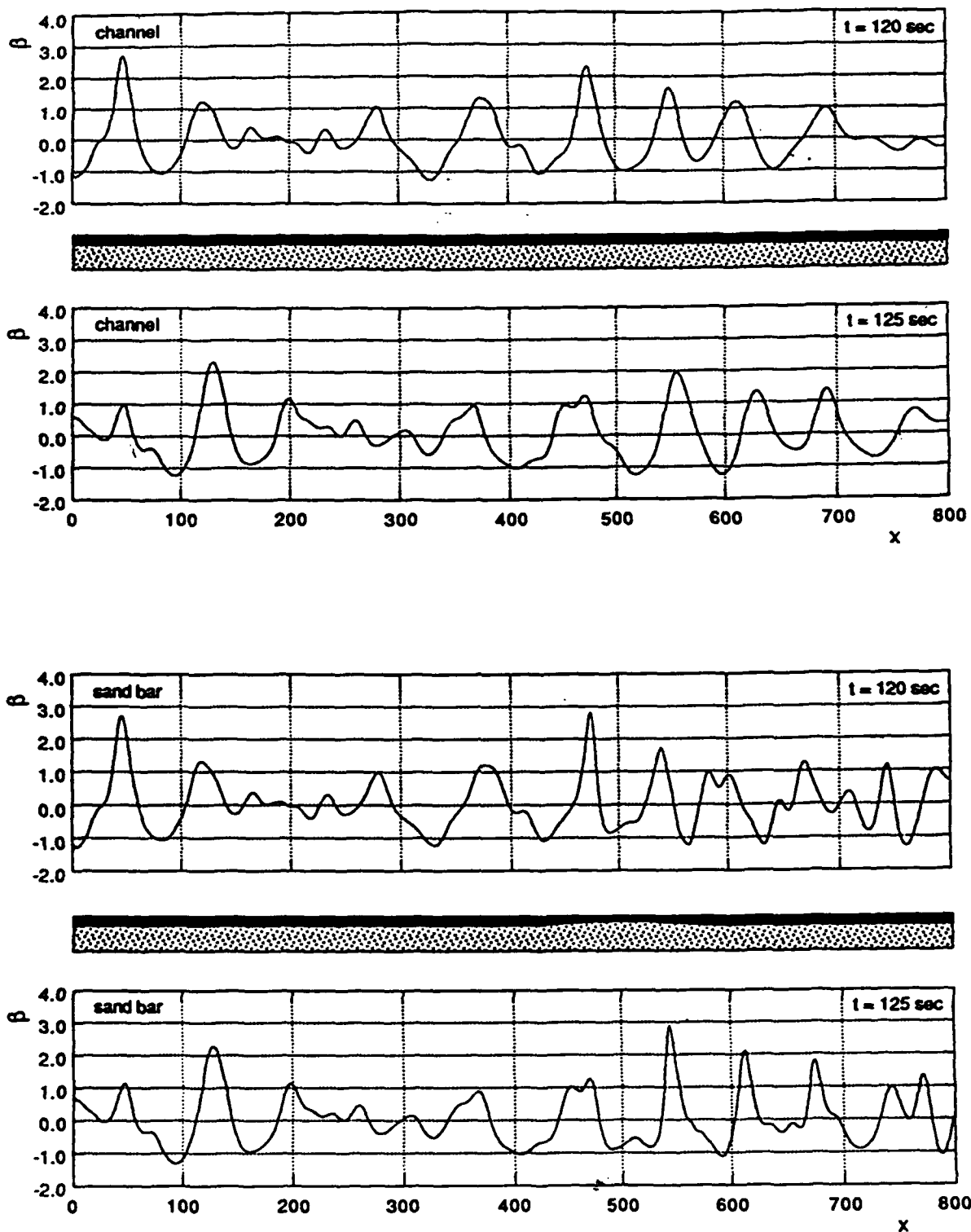


Figure A19. Snapshots of wave profiles at $t = 120$ sec and $t = 125$ sec

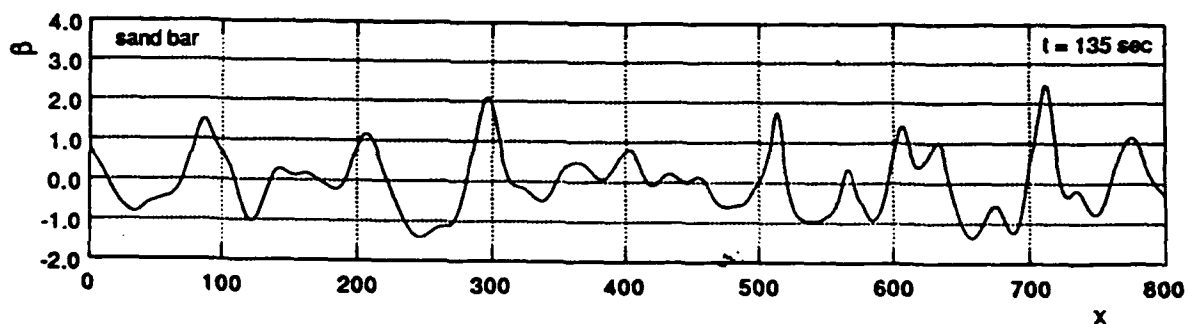
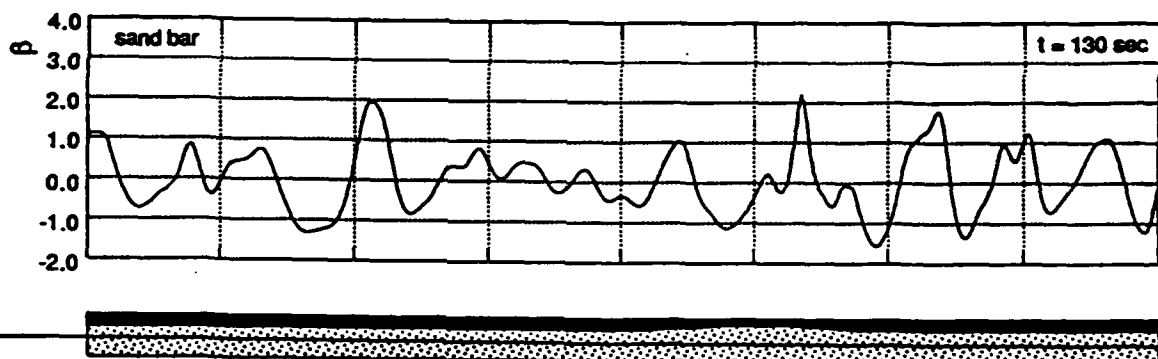
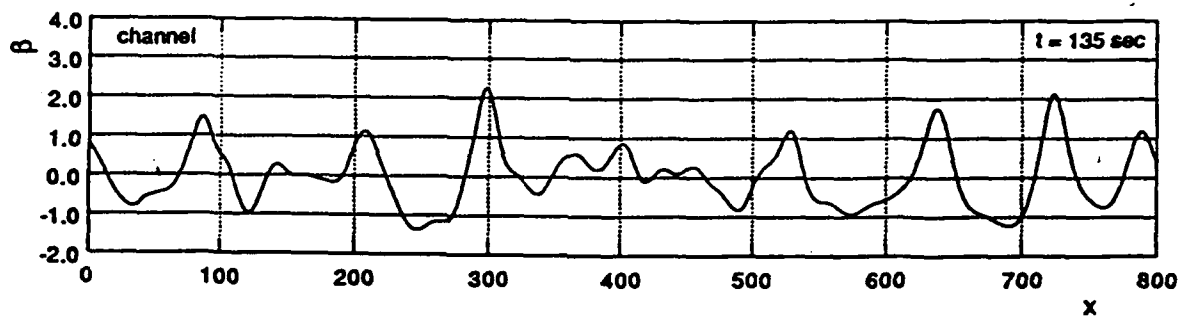
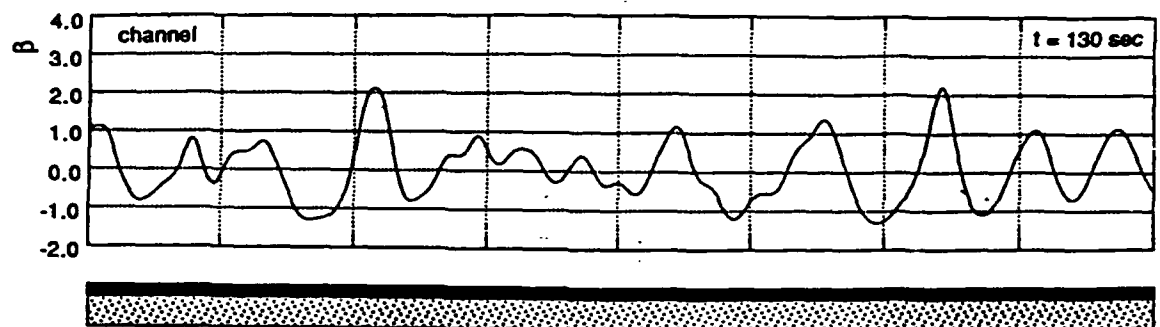
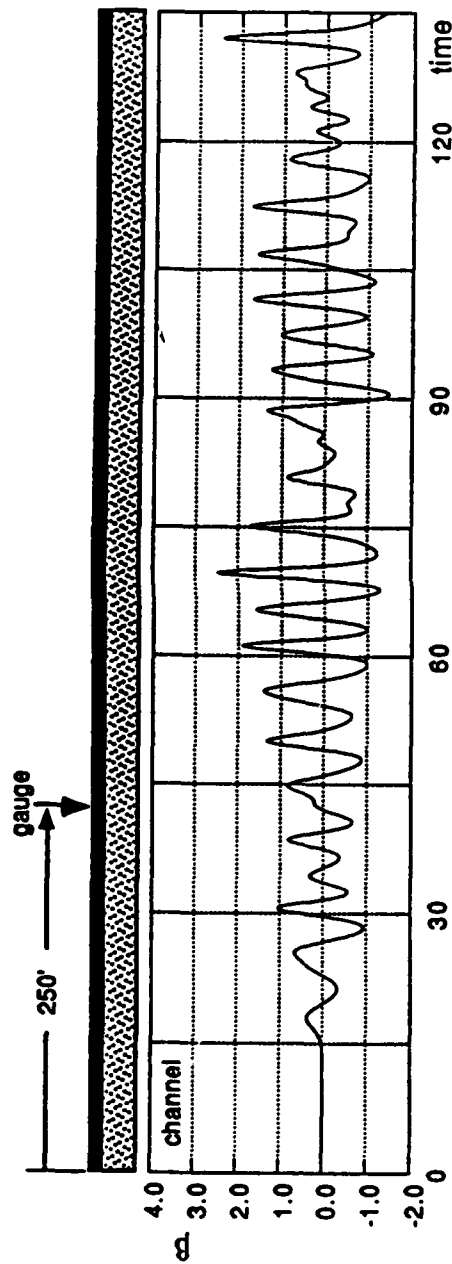


Figure A20. Snapshots of wave profiles at $t = 130$ sec and $t = 135$ sec



A26

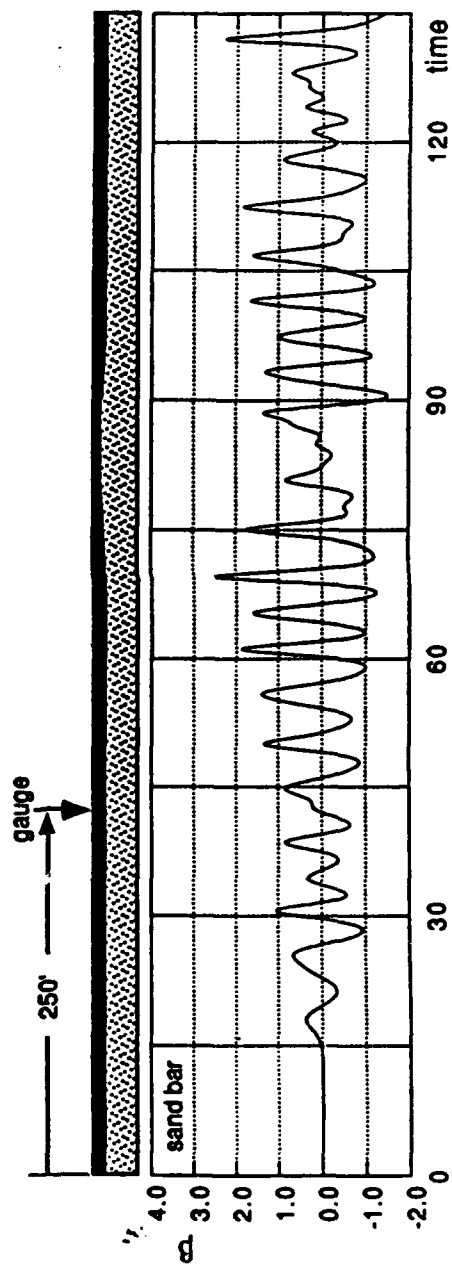
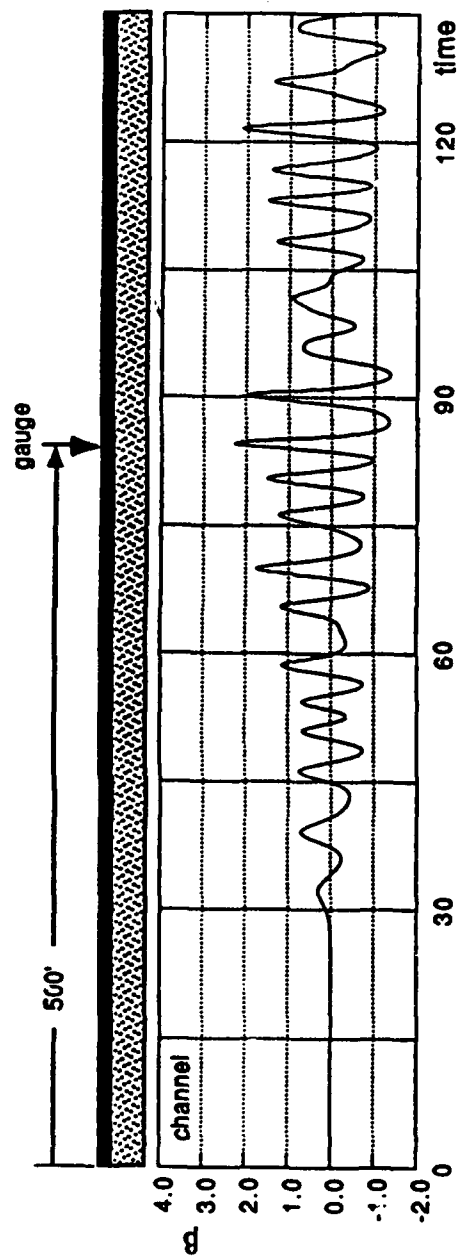


Figure A21. Time histories of wave elevation at $x = 250$ ft



A27

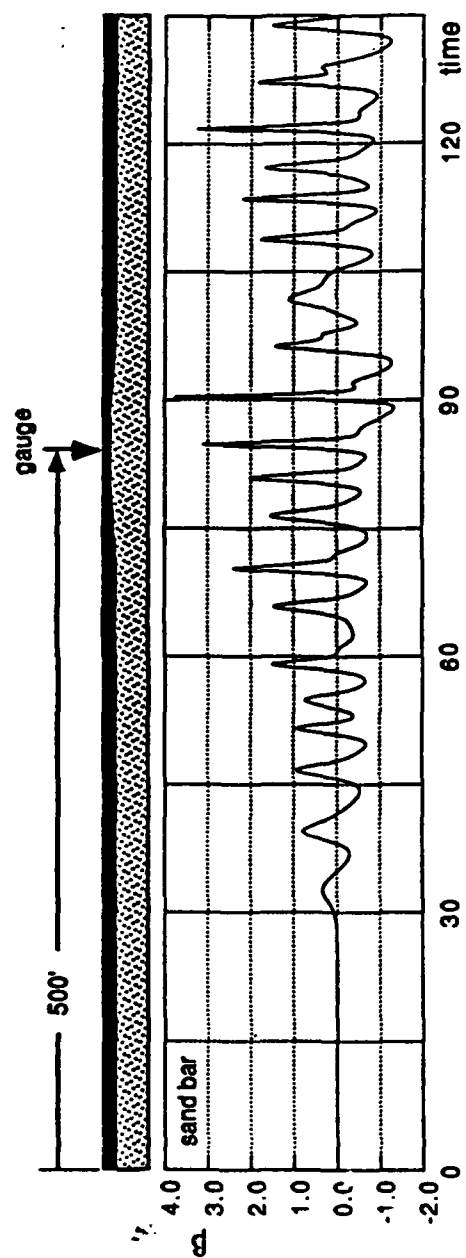
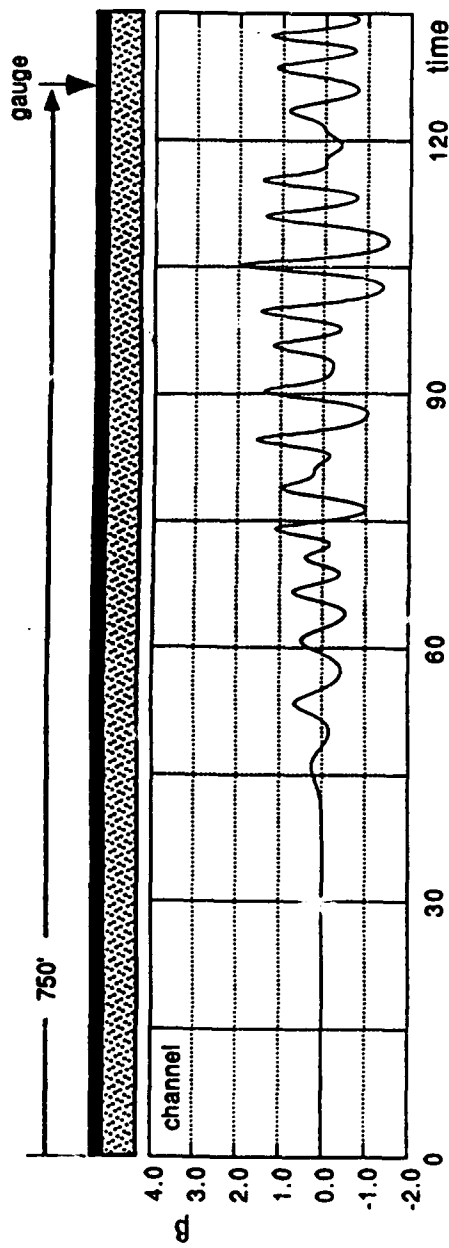


Figure A22. Time histories of wave elevation at $x = 500$ ft



A28

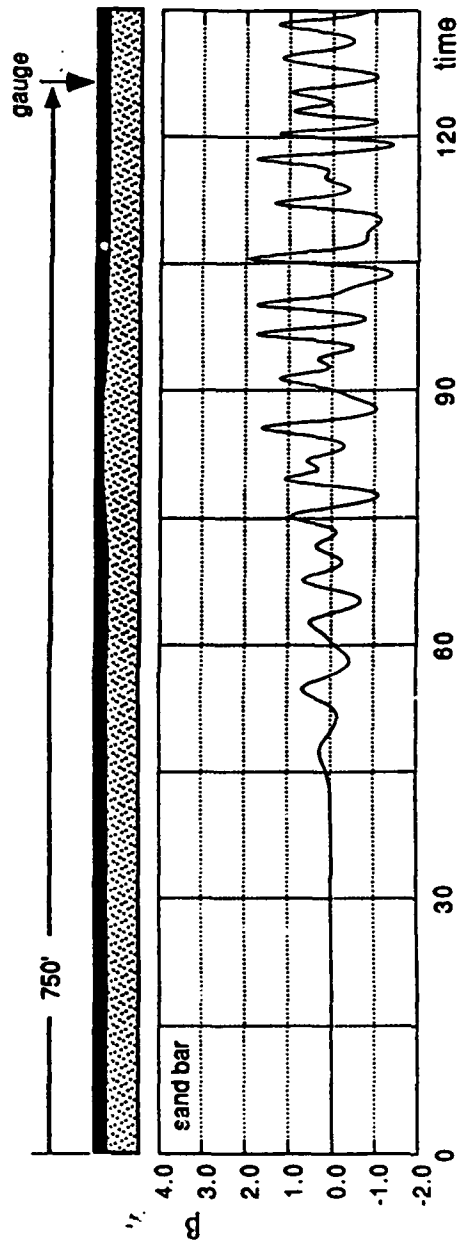


Figure A23. Time histories of wave elevation at $x = 750$ ft

Example IV: Shoaling Waves over a Uniformly Sloped Coastal Beach

As waves approach a beach, they steepen, become unsymmetrical and eventually break. The GN Level II theory which forms the basis of GNWave is not capable of predicting the evolution of waves beyond the breaking stage, but it can predict the evolution almost up to breaking. The example below is identical to that presented in Shields' thesis and models experiments of Hansen and Svendsen (1979) conducted at the Technical University of Denmark. Regular waves are created in a tank 25 m long with a beach that begins 13 m downstream of the wave maker. The beach has a slope of 1:34.26. The water depth at the wave maker is 0.360 m. For the purposes of modeling here, the bottom of the beach is not allowed to pierce the water surface, but is kept at a water depth of 0.040 m from a point 0.02396 m downstream of the beach. The input file for this example problem is listed below in Figure A24.

<p>Hansen & Svendsen Test #031041</p> <p>SI</p> <p>open</p> <p>25.00000</p> <p>20.00000</p> <p>19</p> <p>snap12.0 12.00000</p> <p>snap14.0 14.00000</p> <p>snap16.0 16.00000</p> <p>snap17.0 17.00000</p> <p>snap17.1 17.10000</p> <p>snap17.2 17.20000</p> <p>snap17.3 17.30000</p> <p>snap17.4 17.40000</p> <p>snap17.5 17.50000</p> <p>snap17.6 17.60000</p> <p>snap17.7 17.70000</p> <p>snap17.8 17.80000</p> <p>snap17.9 17.90000</p> <p>snap18.0 18.00000</p> <p>snap18.1 18.10000</p> <p>snap18.2 18.20000</p> <p>snap18.3 18.30000</p> <p>snap18.4 18.40000</p> <p>snap18.5 18.50000</p> <p>5</p> <p>gage280 15.7400 - 0.28000 0.00000 20.00000</p> <p>gage240 17.1100 - 0.24000 0.00000 20.00000</p> <p>gage200 18.4800 - 0.20000 0.00000 20.00000</p> <p>gage160 19.8500 - 0.16000 0.00000 20.00000</p> <p>gage120 21.2200 - 0.12000 0.00000 20.00000</p> <p>3</p> <p>0.00000 - 0.36000</p> <p>13.00000 - 0.36000</p> <p>23.96000 - 0.04000</p> <p>1</p> <p>0.04000 3.33333</p>	<p>Title</p> <p>units (En or SI)</p> <p>rhs b.c. (op or re)</p> <p>x-domain</p> <p>t-domain</p> <p># of snapshots</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p>snapshot title & time</p> <p># of gages</p> <p>gage title, x, depth & times</p> <p>gage title, x, depth & times</p> <p>gage title, x, depth & times</p> <p>gage title, x, depth & times</p> <p>gage title, x, depth & times</p> <p># nodes in profile</p> <p>profile node</p> <p>profile node</p> <p>profile node</p> <p># wave components</p> <p>height, period</p>
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Figure A24. Input file for the shoaling of regular waves

A small sketch of the test situation is shown at the top of Figure A25. Regular waves are generated at the wave maker with a height of 40 mm and a period of 3.33 sec (frequency of 0.3 Hz).

Results and Discussion

Figure A25 shows five wave profiles at times from 17.2 sec to 18.4 sec (the first wave breaks at 18.5 sec). Figure A26 shows the detail of the waves near the beach at 0.1-sec intervals. For these details, the output data (shown as small squares) were fitted with spline curves to yield smooth wave shapes. The sharpening and steepening of the wave is apparent, as is the development of a "shoulder wave" just behind the main crest.

These results, although similar in form to those presented by Shields (1986) are different in some respects. In particular, the waves break further up the beach from the point reported by Shields and that measured by Hansen and Svendsen (1979). An investigation of this was made and it was determined that these discrepancies were due to the built-in facilities in GNWave which yield an easy user interface and do not reflect on either the theory or its general usage.

The first wave in the train is purposely attenuated (or "ramped") and this is appropriate for most problems. In this problem, the first full wave breaks and the computation cannot continue. Thus, although the subsequent waves in the wave train have the required height of 40 mm, the first wave is not quite this high. This causes the wave to break further up the beach from the point determined by Shields and that measured by Hansen and Svendsen (1979). Shields (1986) was able to get around this problem by starting the calculation with an already developed train of regular waves and letting them progress on shore. This way his first wave was at the full height and he was able to compare directly with the experimental results. It is not possible to allow such tinkering with the input waves and still have an easy-to-use program.

Further validation of GNWave with field and laboratory data is in progress.

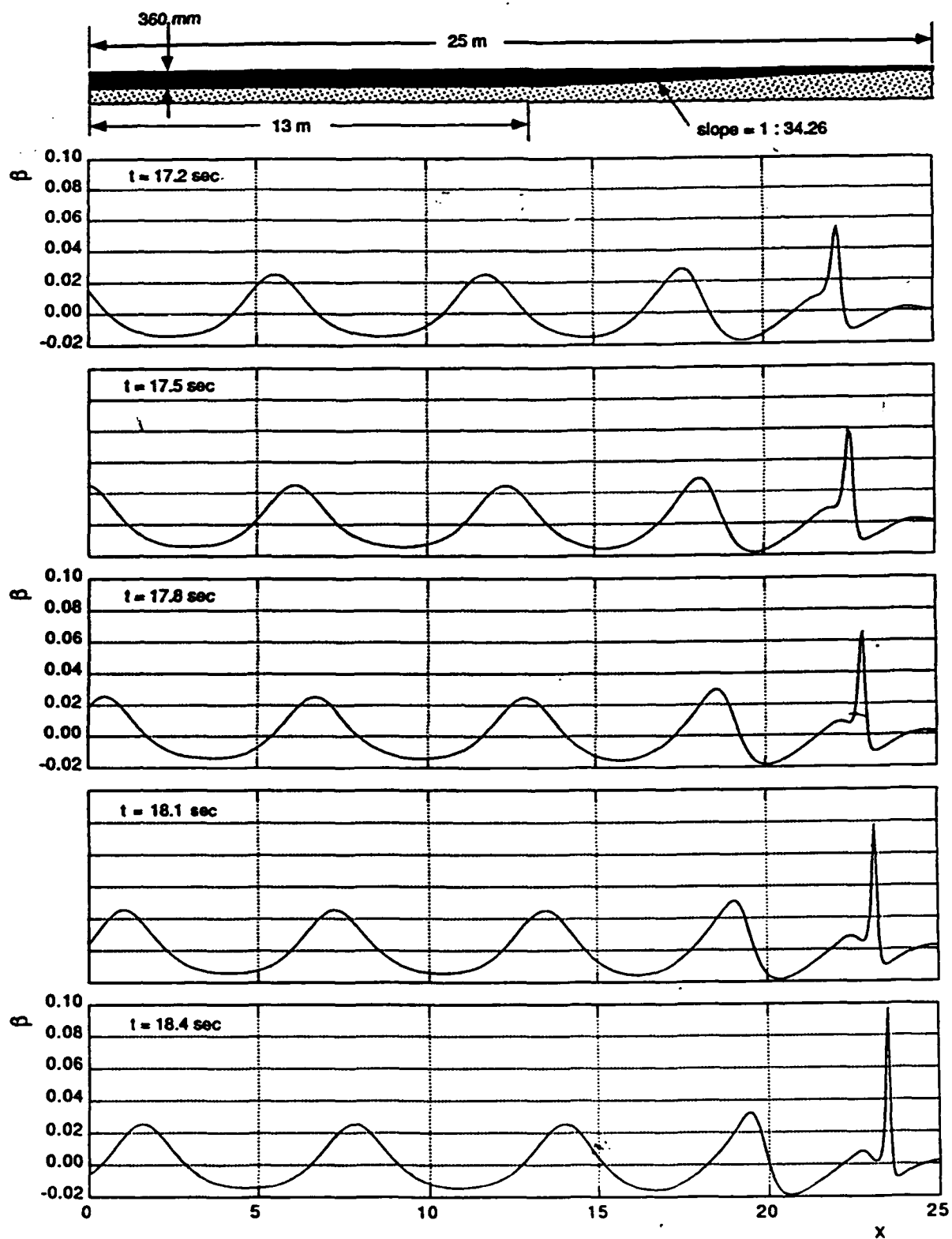


Figure A25. Waves in tank just before first wave breaks

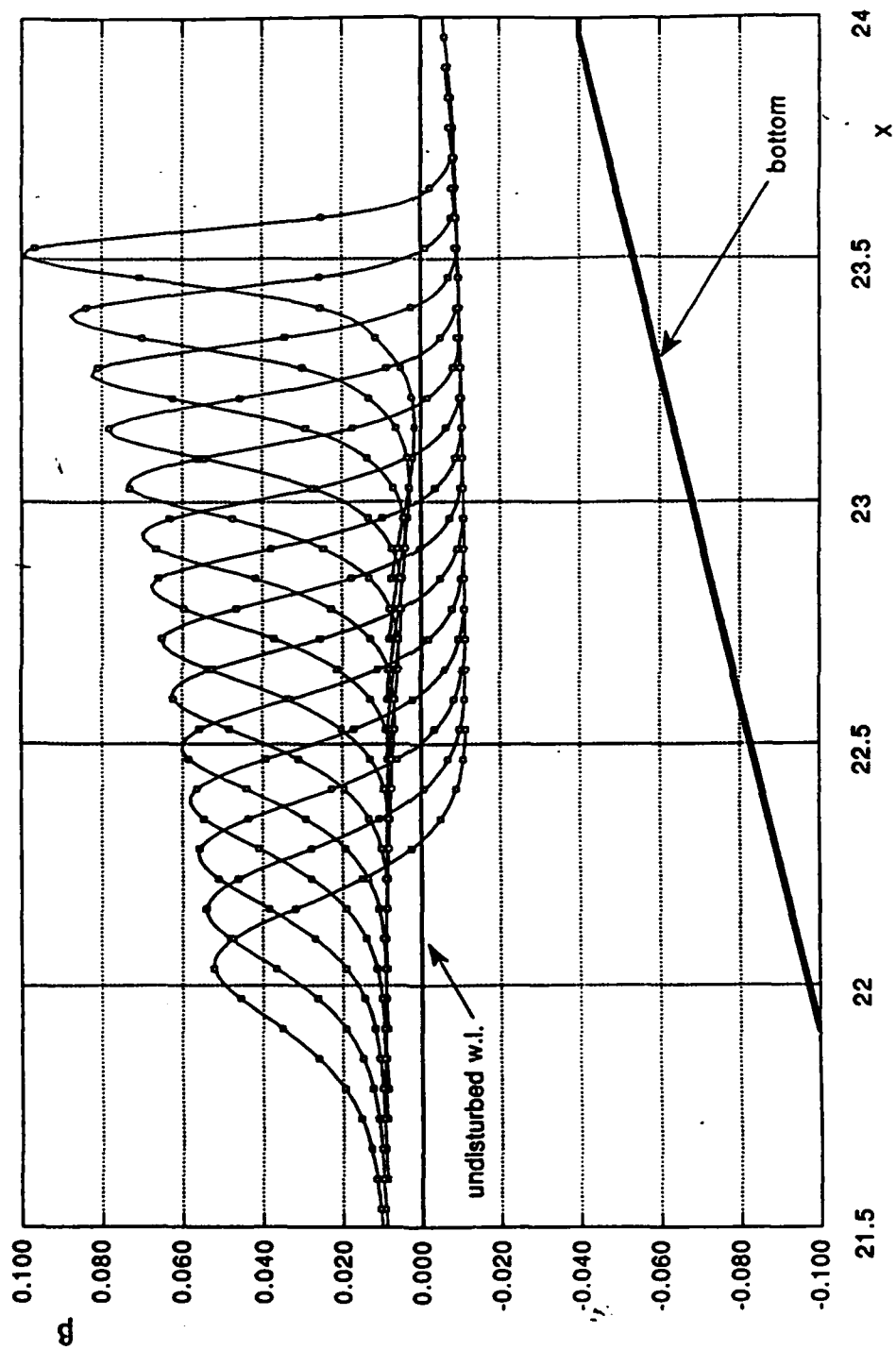


Figure A26. Wave profiles 0.1 sec apart as first wave approaches beach

Waterways Experiment Station Cataloging-in-Publication Data

Demirbilek, Zeki.

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56 p. : ill. ; 28 cm. — (Technical report ; CERC-92-13)

Includes bibliographical references.

1. GNWave (Computer program) 2. Hydrodynamics — Computer programs. 3. Water waves — Mathematical models. Oceanography — Computer programs. I. Webster, William C. II. United States. Assistant Secretary of the Army (Research, Development and Acquisition) III. Coastal Engineering Research Center (U.S.) IV. U.S. Army Engineer Waterways Experiment Station. V. Title. VI. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; CERC-92-13. TA7 W34 no.CERC-92-13